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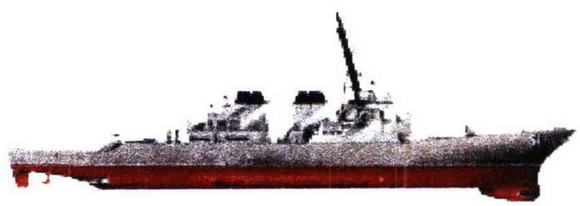
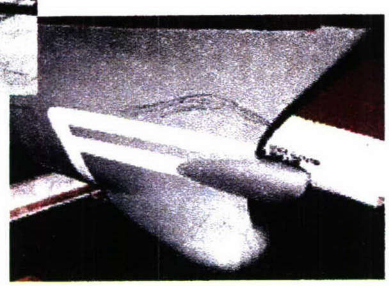
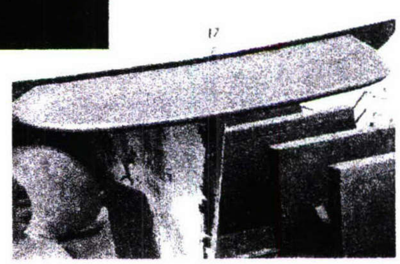
U.S. NAVY SURFACE SHIP FLEET: PROPULSION ENERGY EVALUATION, AND IDENTIFICATION OF COST EFFECTIVE ENERGY ENHANCEMENT DEVICES

By
Dominic S. Cusanelli and Gabor Karafiath



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A powering evaluation of the U.S. Navy surface ship fleet was prepared. This information was used to identify eleven U.S. Navy surface ship classes as candidates for consideration with regard to retrofit of energy enhancement devices. These classes possess worthwhile energy savings potential with the installation of such devices. Potential yearly energy device fuel cost savings, and long and short term potential fuel savings, were then estimated for these identified candidate ship classes.

A large number of energy enhancing concepts and devices with potential for reducing delivered power requirements or improving ship energy efficiency, are identified and described. (continued on next page)

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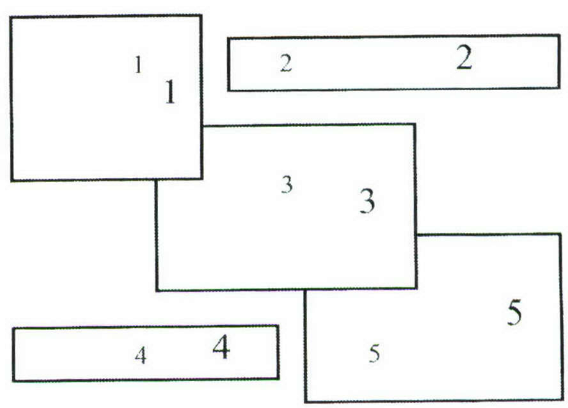
14. ABSTRACT (continued) A chart of compatibility between all identified energy savings devices was prepared. Over a dozen propulsion energy enhancement devices are identified as having potential for retrofit to U.S. Navy candidate surface ship classes.

Recommendations are prepared with regard to which energy enhancement devices are to be considered as cost beneficial for retrofit to each of the eleven identified candidate U.S. Navy surface ship classes.

Front cover design. Descriptions, credits, and acknowledgments.

1. Full scale propeller on PC-13 Class. Energy efficient tip propeller with advanced blade sections. Photograph by author.
2. DDG-51, Arleigh Burke Class. Modified from original artwork appearing on Bath Iron Works Corporation promotional literature.
3. Model scale small, near surface, bow bulb on DDG-51. Photograph by author.
4. LPD-17 Amphibious. Modified from original artwork appearing on LPD-17 world wide web site.
5. Full scale stern flap on FFG-7 Class. Photograph by author.



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NOTATION

The notation contained herein conforms with International Towing Tank Conference (ITTC) Symbols and Terminology List - 1993, except where noted.

INTERNATIONAL STANDARD SYMBOLS (abbreviated)

Conventional Symbol	Computer Compatible (CC) Symbol	Title
C_A	CA	Ship/Model Correlation Allowance
C_D	CD	Drag Coefficient
C_F	CF	Frictional Resistance Coefficient
C_R	CR	Residuary Resistance Coefficient
C_T	CT	Total Resistance Coefficient
C_{Th}	CTh	Propeller Thrust-Loading Coefficient
D	D	Drag (in general)
F_D	FD	Towing Force in self propulsion test
F_n	Fn	Froude number
J	J	Propeller Advance Coefficient (Advance number)
J_V	JV	Apparent (Ship Speed) Advance Coefficient
K_Q	KQ	Torque Coefficient
K_T	KT	Thrust Coefficient
n	n	rate of revolution
P_D	PD	Delivered Power at propeller
P_E	PE	Effective Power
Q	Q	Torque
R	R	Resistance (in general)
R_n	Rn	Reynolds number
t	t	Thrust deduction fraction
T	T	Thrust
V	V	Speed (Velocity) in general
V_A	VA	Speed of Advance of propeller
w_Q	WQ	Taylor Wake Fraction (torque identity)
w_T	WT	Taylor Wake Fraction (thrust identity)
α	ALPHA	Angle (in general)
β	BETA	Advance Angle of propeller blade section

η	ETA	Efficiency (in general)
λ	LAMDA	Model linear scale ratio

NOTATION (continued)

U.S. CUSTOMARY AND METRIC EQUIVALENTS

U.S. CUSTOMARY	METRIC
1 inch	25.4 millimeter [0.0254 m (meter)]
1 foot	0.3048 m (meter)
1 pound (force)	0.4536 kg (kilograms)
1 ft - pound	0.1382 kg - m (kilogram - meters)
1 foot per second	0.3048 m/s (meter per second)
1 knot	0.5144 m/s (meter per second)
1 degree (angle)	0.01745 rad (radians)
1 horsepower	0.7457 kW (kilowatts)
1 long ton	1.016 tonnes, 1.016 metric tons, or 1016.0 kilograms
1 inch water (60°F)	248.8 pa (pascals)

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ABSTRACT

This report identifies U.S. Navy surface ships that would benefit most from the retrofit of hydrodynamic energy enhancement devices. These devices reduce the required power, and consequently, the fuel needed for propulsion. A large number of potential energy enhancement devices are assessed with regard to their suitability and cost effectiveness for retrofit to U.S. Navy surface ships.

A powering evaluation of the U.S. Navy surface ship fleet was prepared. This information was used to identify eleven U.S. Navy surface ship classes as candidates for consideration with regard to retrofit of energy enhancement devices. These classes possess worthwhile energy savings potential with the installation of such devices. Potential yearly energy device fuel cost savings, and long and short term potential fuel savings, were then estimated for these identified candidate ship classes.

A large number of energy enhancing concepts and devices with potential for reducing delivered power requirements or improving ship energy efficiency, are identified and described. A chart of compatibility between all identified energy savings devices was prepared. Over a dozen propulsion energy enhancement devices are identified as having potential for retrofit to U.S. Navy candidate surface ship classes.

Recommendations are prepared with regard to which energy enhancement devices are to be considered as cost beneficial for retrofit to each of the eleven identified candidate U.S. Navy surface ship classes.

ADMINISTRATIVE INFORMATION

The work described in this report was performed at the David Taylor Model Basin, Carderock Division Headquarters, Naval Surface Warfare Center (CARDEROCKDIV, NSWC), herein referred to as DTMB, by the Hydromechanics Directorate, Resistance and Powering Department, Code 5200. The work was sponsored by the Shipboard Energy R&D Office, Code 859, Annapolis Detachment, CARDEROCKDIV, NSWC, Sponsor R823, Task Area R0829, Element No. 0603724N, job order number 1-8590-537.

INTRODUCTION

The Shipboard Energy R&D Office has requested the Resistance and Powering Department to identify hydrodynamic energy enhancement devices that could be used by the U.S. Navy surface ship fleet. These energy enhancement devices would reduce the power required for ship propulsion for the purpose of reducing fuel consumption.

The data reported herein is divided into three topic areas. The first is a compilation of the propulsion energy usage evaluation of the present U.S. Navy surface ship fleet. The second topic area is descriptive information on a large number of energy enhancing concepts and devices, and an assessment with regard to their suitability for retrofit to U.S. Navy surface ships. Third, recommendations are prepared with regard to

which energy enhancement devices are to be considered as cost beneficial for retrofit to U.S. Navy surface ship classes.

The reason for the U.S. Navy surface ship fleet evaluation, presented in Appendix A, is to identify those ships or ship classes that will use the most fuel during their remaining service life. From an economic point of view, the ship classes that use the most fuel, and will do so over a long remaining service life, will tend to be the primary candidates for the retrofit of energy enhancement devices. Small percentage gains in propulsion efficiency can result in very large total fuel cost savings on these classes. Furthermore, for ship classes with a large number of identical ships, the design, model testing, and ship trials costs, can be spread out over many ships, so that the actual cost per ship can be reduced dramatically. In addition, the retrofit of any energy enhancement device may become significantly less expensive through subsequent installations on identical ships. This reduction in installation cost is due to the traditional "learning curve" effect associated with ship integration and construction. Thus, within the U.S. Navy surface ship fleet evaluation, it was important to identify those ships that used a large amount of fuel, had a large number of identical ships in their class, and had a significant amount of service life remaining. Eleven U.S. Navy surface ship classes are identified as potential candidates for the retrofit of an energy saving device.

Appendix B is a compilation of many energy saving ideas, concepts, and devices, that have been developed or considered by the U.S. Navy, or by the commercial ship industry. Many of the devices depicted could be considered the hypothetical energy saving device of the economic analysis presented in Appendix A. Depictions of these devices, as well as some cursory explanations as to the underlying physical principles of operation are presented. A chart of compatibility among energy savings devices has been prepared. An assessment is made with regard to the practicality of retrofitting each device to a U.S. Navy surface ship hullform. Based upon hydrodynamic performance, approximately 14 energy enhancement devices are identified as potential candidates for retrofit. An extensive listing of references documenting the development and performance of the energy savings ideas, concepts, and devices, is also provided as Appendix C.

The third part of this report is a recommendation in regard to which of the fourteen selected energy enhancement devices are to be considered as cost beneficial for retrofit to each of the eleven identified candidate U.S. Navy surface ship classes. Many practical considerations beyond suitability, such as cost (R&D, ship integration, manufacturing, and installation), availability of devices with greater potential, technical risks, etc., were taken into account in making these recommendations.

PRIMARY MEANS OF ENERGY REDUCTION

For any ship design, the primary means, by which to save shipboard energy, is the correct sizing and design of the vessel and its propulsor, Schneekluth (1)[1]. During the initial design, basic ship optimization must be considered in the areas of hullform dimensions such as length, beam, and draft, and the hullform shape parameters such as block coefficient and prismatic coefficient. In addition, it is important that the propeller(s) be sized and designed to operate efficiently with the hull and with the main propulsion engine. The critical nature of this sizing and design process is emphasized and explained in Ref. 1. Even within identical size and shape parameters, there exists the opportunity to design superior hullforms. Appendix B identifies some features and design procedures for reduced energy hullforms. Some hull shaping features can only be implemented during new construction while other features such as bulbs, flaps, and wedges, are suitable as either new design or retrofit. The emphasis of this report will be on retrofit devices suitable for existing U.S. Navy surface ships.

U.S. NAVY SURFACE FLEET EVALUATION

The collected information on the existing U.S. Navy surface ship fleet is presented in Appendix A. A summary is provided in this section. For presentation purposes, the U.S. Navy surface ship fleet is separated into five main surface force classifications: (A) Surface Combatants, (B) Amphibious Warfare Ships, (C) Fleet Auxiliary Force, (D) Mine Warfare, and (E) Active Strategic Sealift. Ships or ship classes in each of the main ship functional force classifications are further subdivided into nineteen (19) categories separated by ship type (ship function). Nearly sixty (60) active surface ship classes were identified.

The four new TAKR sealift ship classes are not included in the above compilation because their initial deployment is intended for Maritime Preposition ships or Ready Reserve Force ships that are in port most of the time. If the deployment of these ships changes to predominantly underway operations then it will be appropriate to consider them for propulsion energy enhancement devices.

The nearly 60 active surface ship classes were ranked according to how much propulsion fuel each ship class would use during their remaining service life. Actual fuel consumption data on all ships of the U.S. Navy is not readily available, therefore a relative future fuel usage index, defined by the product of installed propulsion power, number of ships in a class, and remaining service life was established.

US Navy surface ship classes were then selected from Appendix A as appropriate candidates for the retrofit of an energy savings device. The selected candidates were those classes that tended to have a large number of identical ships in their class, had a high fuel usage, and had a significant amount of service life remaining. These candidate ship classes would have the highest potential life-cycle fuel savings with the

[1] References are listed on page 23

installation of energy savings device. The annual potential fuel cost savings, attributed to the installation of a hypothetical energy savings device, was then determined for each of the 11 identified candidate ship classes. It was assumed that this energy savings device would effect a 5 percent annual fuel savings. The annual fuel cost savings was then carried through the remaining service life for each class, and the potential life-cycle fuel savings was determined for the hypothetical 5% energy savings device. The eleven selected candidate U.S. Navy surface ship classes are shown below:

Table 1. Eleven selected candidate U.S. Navy surface ship classes

SELECTED CANDIDATE SHIP CLASSES FOR ENERGY DEVICE RETROFIT		
US Navy Surface Ship Class	Number of Ships in Class *	Potential Class Life Cycle Fuel Savings from 5% Device
(A) Surface Combatants		
Ticonderoga, CG 47	27	$ 129 M
Spruance / Kidd, DD 963 / DD 993	35	$ 84 M
Arleigh Burke, DDG 51	50	$ 283 M
Oliver Hazard Perry, FFG 7	35	$ 55 M
(B) Amphibious Warfare Ships		
San Antonio, LPD 17	12	$ 49 M
Wasp, LHD 1	6	$ 45 M
Tarawa, LHA 1	5	$ 18 M
Whidbey Island / Harpers Ferry, LSD 41 / LSD 49	12	$ 24 M
(C) Fleet Auxiliary Force		
Henry J Kaiser, TAO 187	16	$ 59 M
Cimarron (Jumbo), AO 177	5	$ 10 M
Supply, AOE 6	4	$ 23 M
* Number of ships in class presently active or planned. CG 47, DD 963, and DD 993, share the same hullform		

According to the above table, the most savings are associated with the destroyer and cruiser classes, and the next largest savings are associated with the TAO 187 class.

Table 2 shows some general characteristics of these selected U.S. Navy ship classes. The type of prime mover will have an influence on the amount of fuel saved for a given reduction in delivered power achieved through the retrofit of a hydrodynamic energy saving device. In general, for diesel and for steam power plants, there is an almost 1 to 1 correspondence between decreased delivered power and decreased fuel consumption. However, the general experience based on fuel calculations for gas turbine ships, has been that a 1% decrease in delivered power results in only a 0.7 % decrease in fuel usage. Thus with all other

factors being equal, a given hydrodynamic device will be more effective in terms of % fuel saved on a diesel or steam driven ship than on a gas turbine driven ship.

Table 2. General characteristics of the eleven selected U.S. Navy surface ship classes

SELECTED CANDIDATE SHIP CLASSES GENERAL CHARACTERISTICS						
Ship Class	Prop Type	Prime Mover	Bow Type	Max Speed	Rudder Type	Shafting Appendages
CG 47	CP-2	GT	NB, BSD	31	2-spade	Shaft & Strut
DD 963 / DD 993	CP-2	GT	NB, BSD	31	2-spade	Shaft & Strut
DDG 51	CP-2	GT	NB, BSD	32	2-spade	Shaft & Strut
FFG 7	CP-1	GT	NB, KSD	30	1-spade	Shaft & Strut
LPD 17	FP-2 (CP?)	D	BB	23	2-horn	Shaft & Strut
LHD	FP-2	S	BB	25	2-spade	Shaft & Strut
LHA	FP-2	S	NB	25	2-spade	Shaft & Strut
LSD 41 / LSD 49	FP-2	D	BB	23	2-spade	Shaft & Strut
TAO 187	CP-2	D	NB	22	2-horn	Shaft & Strut
AO 177 (J)	FP-1	S	BB	22	1-spade	Closed Skeg
AOE 6	FP-2	GT	BB	30	2-spade	Shaft & strut

Prop Type: Controllable Pitch (CP), Fixed Pitch (FP), Single screw (-1), Twin Screw (-2)
Prime Mover: Gas Turbine (GT), Diesel (D), Steam (S)
Bow Type: No Bulb (NB), Bulbous Bow (BB), Bow Sonar Dome (BSD), Keel Sonar Dome (KSD)
Max Speed: Approximate Maximum Speed in Knots

The cost of the hypothetical 5% energy saving device was separated into low, median, and high cost categories, to reflect realistic cost differences associated with simple versus complex devices. The net cost savings, equal to the fuel savings over the ship service life minus the device retrofit cost, was calculated for each selected ship class. The device retrofit cost included design, model testing, construction, and ship trials costs. Construction and installation did not include dry docking costs. The net cost savings were then calculated through three net cycle term lengths (periods of time). These three terms were: a short term (5 year) net cycle, a median term (10 year) net cycle, and ultimately the remaining service life cycle. All of the above selected candidate ship classes show a positive net cost savings after 5 years of operation with a "low" cost retrofit device (see Fig A6), and a net positive lifetime cost savings even with the "high" cost device (see Fig A8). This simple cost analysis was performed using constant dollars.

SELECTION OF ENERGY SAVINGS DEVICES

The compiled information on many energy enhancing concepts and devices is presented in Appendix B. The information generally includes the following: Depiction of the geometry or general appearance of the device (including photographs, drawings, and/or sketches), mechanisms or principles of operation, practical

considerations, full scale applications or model scale experiences, possible delivered power (or fuel) reduction potential, and mention of prominent references, where available.

The specific identified devices were grouped into three main categories: (A) HULL, (B) APPENDAGE(s), and (C) PROPULSOR(s). Groupings were made so that similar devices, or devices that performed under similar principles of operation, were organized together. This resulted in a total of thirty-five (35) organizational groups of energy savings devices.

From the 35 energy device groups, fourteen (14) were selected for potential retrofit to U.S. Navy surface ships. The selected retrofit energy savings devices for identified U.S. Navy classes are listed in Table 3:

Table 3. Selected retrofit energy savings devices for identified U.S. Navy ship classes

SELECTED RETROFIT ENERGY SAVINGS DEVICES	
Energy Savings Device	Selected for Study and/or Retrofit on U.S. Navy Classes
<u>Category (A) Hull</u>	
Bulbous Bow, Traditional	TAO 187, LHA 1, FFG 7
Bow Bulb, Small, Near-Surface	DDG 51, CG 47/DD 963/993, FFG 7, TAO 187, LHA 1
Stern End Bulb	Recommend R & D for destroyer / frigate hullforms, other likely candidates are TAO 187, AO 177, AOE 6
<u>Category (B) Appendage(s)</u>	
Stator Upstream of Propeller	LHA/LHD, TAO, LSD
Main Strut Barrel Designs	Probably not a feasible retrofit
Alternative Rudder Designs	Recommend flow visualization tests, most likely candidates are TAO 187, AO 177, AOE 6
Thrusting Fins on Rudder(s)	Recommend flow visualization tests, most likely candidates are TAO 187, AO 177, AOE 6
Stern Flap, Stern Wedge	Design Developed for DDG 51, CG 47/DD 963, FFG 7, LPD 17, Investigate for LHD 1, LHA 1, LSD 41&49 and TAO
<u>Category (C) Propulsor(s)</u>	
New Propeller Design	LSD 41 & 49, and possibly AOE 6
Low RPM / Large Diameter Propeller	May not be practical as retrofit
Energy Efficient Tip Propeller	R & D design efforts, LSD 41 & 49
Propeller Fairwater Designs	Recommend flow visualization tests, most likely on DDG 51, CG 47/DD 963/993, FFG 7, LSD 41&49, TAO 187
Fins (Blades) on Propeller Hub	Possible application to all 11 selected ship classes. Recommend to explore retrofit on auxiliary ship.
Propeller Pitch Scheduling	Highly recommend for study and adoption on all ships with controllable-pitch propellers: DDG 51, CG 47/ DD 963/993, FFG 7, LSD 41&49, TAO 187

The selection criteria for the energy savings devices was as follows:

- (1) The device had to be practical as a retrofit.
- (2) The device had to be reliable and durable enough for use on U.S. Navy ships.
- (3) The device had to have a history of demonstrated energy enhancement potential (model or full scale) on some ship similar to a possible U.S. Navy present or future application.
- (4) The energy savings devices had to be applicable to at least one of the U.S. Navy ship classes identified in the first part of the study, or had to be applicable to foreseeable future Navy hullforms. Devices suitable to only high block coefficient, relatively slow speed, commercial or merchant type hulls, with single-screw heavily loaded propellers, were not selected.

The energy savings devices, listed in Table 3, initially satisfied all of the aforementioned criteria.

ENERGY DEVICE APPLICATIONS TO U.S. NAVY HULLFORMS

The following are recommendations with regard to which of the 14 selected energy enhancement devices are to be considered as cost beneficial for eventual retrofit and/or study on the 11 identified candidate U.S. Navy surface ship classes. For this evaluation, the ship classes of CG-47, DD-963, and DD-993, are treated as one class, because they share the same hullform and propeller design, with only minor differences in the propeller shafting and appendage sizes.

Traditional and Small Near Surface Bow Bulb, Stern End Bulb, Stern Flap, and Stern Wedge, are grouped together for discussion purposes because they all act to reduce the wave resistance portion of the ship resistance. They can also affect the form drag, eddy-making, and/or local pressure distribution on the hull. Nevertheless, they all affect the wave drag, and their speed range of effectiveness can be crudely characterized by the ship Froude number, F_n, based on length. In addition these devices tend to be more effective on ships which have a large wavemaking drag component.

It is dangerous to generalize about the performance improvement of these devices, nevertheless empirical evidence indicates that bow bulbs can start to reduce resistance at F_n as low as 0.16 to 0.18, and they become more effective as the speed is increased. We do not have enough experience to generalize about the range of effectiveness of stern end bulbs. Stern flaps can start to reduce resistance at F_n as low as 0.2. Stern flaps tend to improve performance slightly more than wedges. Model test data on the resistance reduction due to stern flaps is shown in Figure 1 for some previously tested combatant, amphibious ship, and sealift models, Cusanelli and Forgach (2).

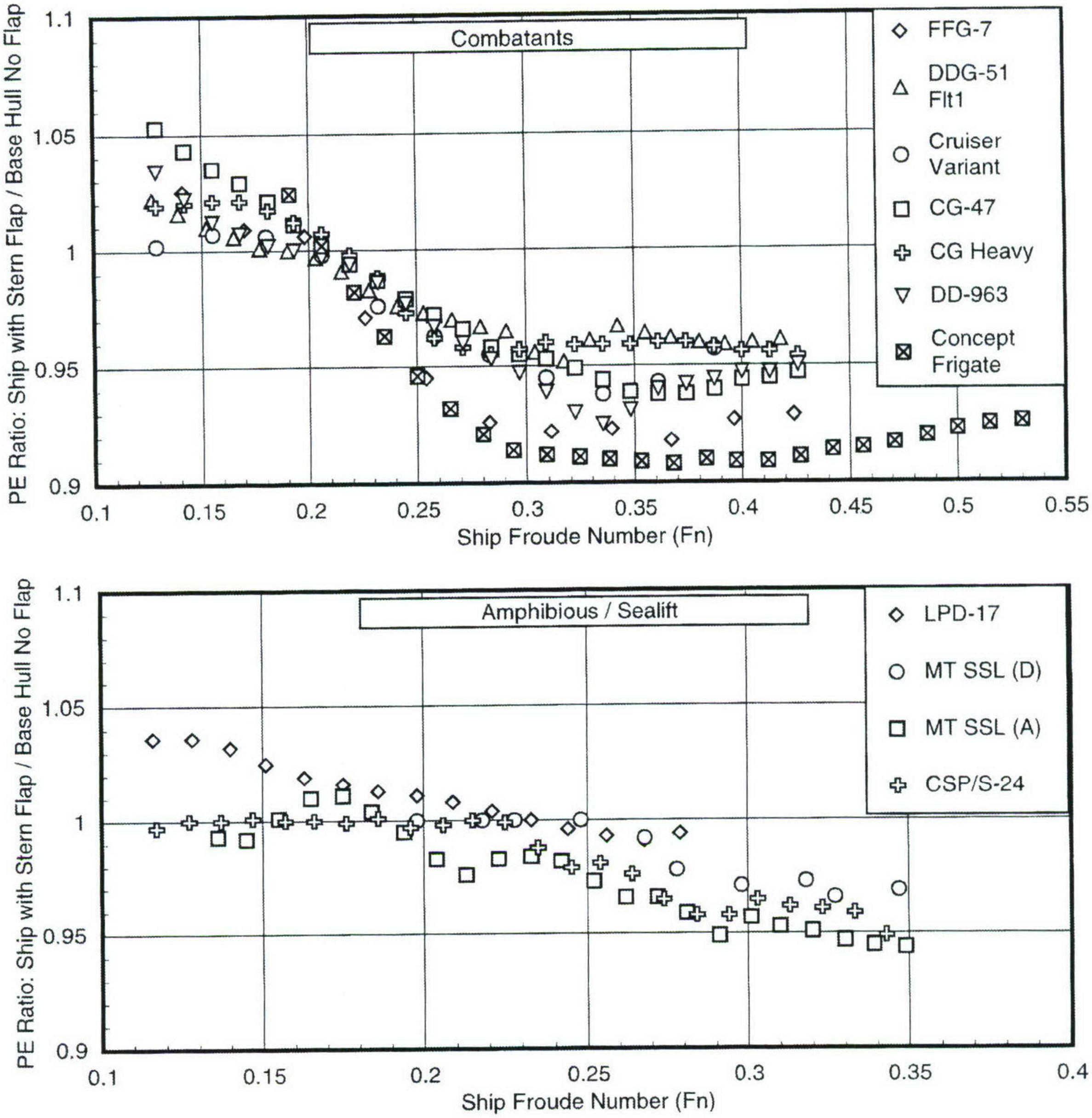

Figure 1. Resistance reductions due to stern flaps

In addition, many cases of model tests show that the powering reduction due to a stern flap can be more than the resistance reduction, possibly 1 to 2 % more. Full scale trial data tend to indicate that the full scale performance improvement due to a stern flap is better than the model scale performance improvement, especially at low speeds, Cusanelli and Cave (3) and Cusanelli (4).

Bare hull resistance information on 9 of the 11 selected hullforms is shown in Figure 2. Three spots are shown for each ship, a near maximum speed, a representative mid-speed, and the lowest speed that was judged to be of interest in terms of energy consumption. The Residuary resistance, C_R,

represents the sum of wave resistance, eddy-making, viscous-wave resistance interaction, and some hullform effect. In most cases, the wave resistance is by far the largest component. The total resistance coefficient, C_T, represents the sum of C_R, the calculated frictional resistance C_F, and the correlation allowance, C_A, determined from full scale trials and model test data. C_A is assumed to be mostly a frictional resistance. Thus the ratio C_R/C_T shown in Figure 2, represents the percentage of ship resistance that is mostly wavemaking in nature, and could be affected by bulbs, flaps, and/or wedges. The LHD bare hull data was not available. The LHD would exhibit resistance close to that of LHA, except that it would be lower for the two highest speeds shown, and higher at the lowest speed point, because the LHD has a bulb.

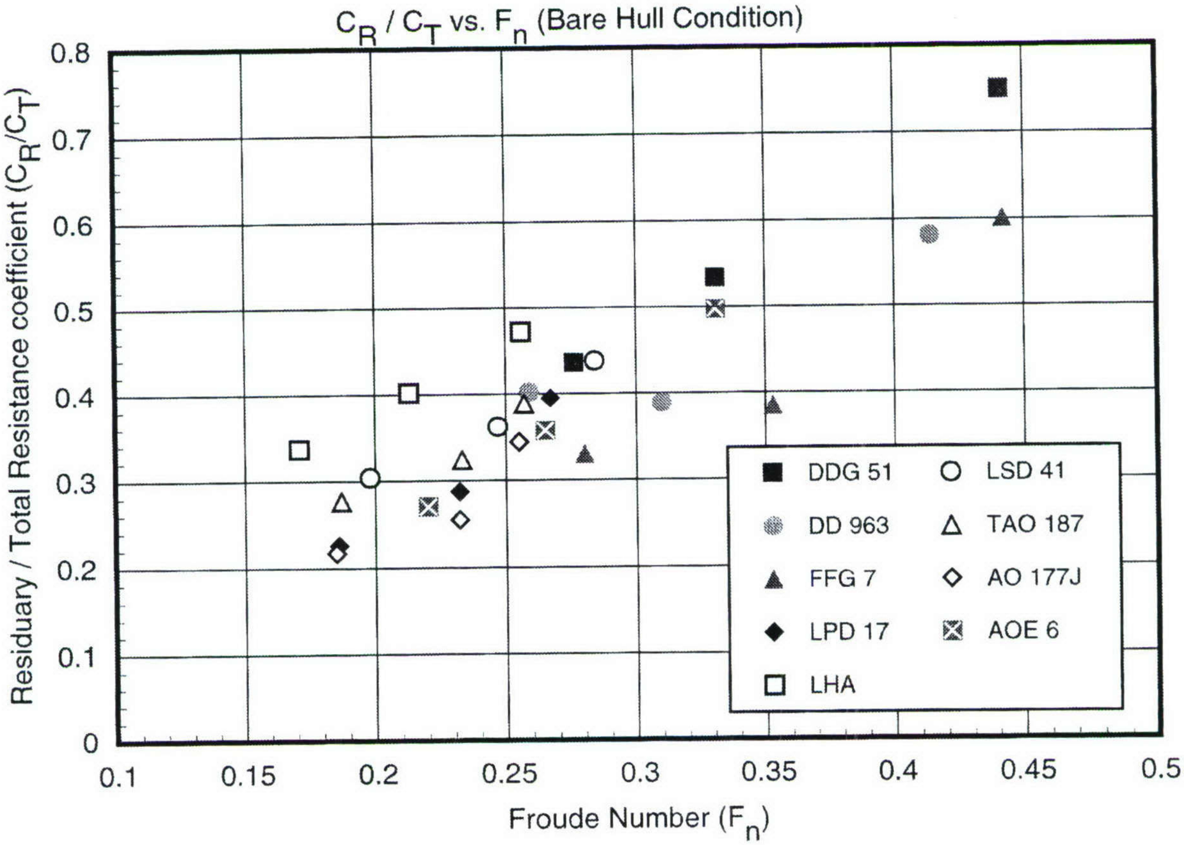

Figure 2. Bare hull residuary resistance for selected U.S. Navy hullforms

Specific recommendations and discussion with respect to Figure 2 is as follows:

Bulbous Bow, Small Near Surface and Traditional:

The design/model test effort involving bow bulbs should investigate both the traditional and small near surface bows. The small bow will be a less expensive retrofit.

• DDG 51, DD 963, CG 47 Classes: The small, near-surface bow bulb is highly recommended for retrofit on these classes. This bow bulb design was developed as a retrofit device for U.S. Navy

indicate a 2 percent delivered power reduction, Cusanelli (6). It is expected that with continued design refinement, the delivered power reduction of this device on the CG 47 or DD 963, would approach that of the DDG 51. The DDG 51 is currently under consideration for a near surface bow bulb. DD 963 / CG 47 efforts should wait until the DDG 51 program is complete.

• TAO 187 Class: A bulbous bow is highly recommended for retrofit on the TAO 187 Class. Previous 1980's model experiments on the TAO with a traditional bulb showed adequate powering reduction at design displacement but a powering penalty in the ballast condition. A newer traditional type bulb design, as developed in the AE 36 Energy Enhancement program, and also in the Sealift Technology Development program, should be tried. In addition, a near surface type retrofit bow bulb, such as developed for DDG 51, should be tested. All bulb designs have to take into account ballast operations. The C_R/C_T plot, of Figure 2, shows that there is potential for improvement, and that the operating F_N is high enough.. A previous 1980 U.S. Navy study concluded that the anticipated fuel cost savings due to retrofitting bulbous bows would be sufficient to justify bulb fabrication and installation costs on some similar ship classes that today are near the end of their service life, Slager and Fung (7).

• FFG 7 Class: The energy saving, with either the traditional or near surface bulb, would be similar or slightly greater than the 4% shown by the current DDG 51 bulb retrofit model tests. Both the small, near-surface bow bulb, and traditional bow bulb, should be explored. Particular emphasis should be placed on avoiding bubble sweepdown on the keel mounted sonar.

• LHA Class: From a hydrodynamic point of view, the LHA class is an ideal candidate for bulb retrofit. The LHD has the same hullform, except that it has a traditional bulb. A small, less expensive near surface bulb, should be considered for the LHA, in lieu of the traditional bulb already on the LHD.

• Other Hull Forms: The hullforms of the other classes such as LPD 17, LHD 1, LSD 41, AO 177 J, and AOE 6, all have bulbous bows.

Stern End Bulb:

There is insufficient experience with stern end bulbs to generalize F_n speed ranges where they would be effective. One would expect wave resistance reduction for a speed range similar to that of bow bulbs and stern flaps. In addition, stern end bulbs are expected to reduce the eddy-making drag, and drag due to excessive vorticity associated with the transom flow, bilge vortex, or propeller wash. This eddy-making drag reduction is probably not as dependent on F_n. The stern end bulb will increase the total wetted surface. Thus, for a stern end bulb to be effective, the combined resistance reduction associated with wave making and eddy-making must be greater than the friction drag associated with the increased wetted surface.

The experience with stern end bulbs (SEBs) is mostly that which is reported from overseas model tests and ship retrofits on just a few merchant ships. There is no U.S. Navy full scale experience with stern end bulbs, or verification of the performance associated with these overseas designs. However, U.S. Navy model experiments were conducted with a similar concept on an Escort Research ship, which had a large single centerline underwater pod aft. The combined effect of the aft pod (i.e. stern end bulb), and of a large forward protruding bow bulb, was to reduce power significantly at high speeds and to increase power at low speeds. Also, initial preliminary design stern end bulbs were model tested on the AOE 6 and the Mid-Term Sealift. Model scale experiments indicated performance ranging from increased power to approximately 2% reduction, depending on ship configuration. These were first design iteration SEBs, and continued design refinement could result in better performance.

A stern end bulb is more expensive to retrofit than a stern flap. However, the stern end bulb could possibly be designed to be effective in both ballast and in the design displacement conditions, whereas the flap could be out of the water in the ballast condition. On the amphibious ships, the stern end bulb may be incompatible with welldeck operations. The recommendation would be to consider stern end bulb hydrodynamic analysis and exploratory R&D on the fuller body ships (TAO 187, AO 177, AOE 6); or on the combined effects of a stern flap with a stern end bulb on the destroyers and cruisers.

Stern Flap, Stern Wedge:

Emphasis should be placed on stern flap design, as they have been shown to perform better than wedges in recent comparative model testing. The U.S. Navy has retrofitted stern flaps on two FFG 7 Class frigates, and verified full scale performance improvements, Cusanelli and Cave (3). Stern flap performance improvements, demonstrated on Patrol Coastal PC 13, has lead to the Navy's plan to retrofit flaps on the entire PC 1 class, Cusanelli (4). An investigation is underway to quantify the energy savings with stern flaps on the DD 963 ,CG 47 and DDG 51 Flight 1 and Flight 2 class ships, and to install a flap on a DD 963 class in FY97. Stern flaps will be featured on the new LPD 17 and DDG 51 Flight 2A ships. Several model tests have shown powering benefits with stern flaps on larger, sealift type ships operating near their design speeds. The ease of ship integration, low costs of R&D and ship installation, and proven performance improvements, make this device ideal for retrofit.

• DD 963, CG 47, DDG 51, FFG 7, LPD 17 Classes: The recommendation is to complete the stern flap work currently funded.

• LHA, LHD, LSD 41/49 Classes: Using the $F_n \geq 0.2$ criteria for effectiveness of a stern flap at low speed, a stern flap will be effective for speeds of 16.2 to 22.8 knots for LSD, and for 18.7 to 24.4 knots for the LHA / LHD. The upper speeds represent the maximum trials speeds. Stern flap design needs to

consider amphibious operations and stern gate deployment. Stern flap design for these ships is recommended. The low deadrise transom shape is suitable for stern flaps.

• TAO 187, AO 177 J, and AOE 6: Again using the aforementioned $F_n \geq 0.2$ criteria and the maximum trials speed, stern flaps would be effective on these ships at the following speed ranges; 17.1 to 22.2 knots for the TAO, 17.3 to 22 knots for the AO, and 18.1 knots to 30.3 knots for the AOE. However, none of these ships are ideal candidates for a traditional stern flaps, because, they all operate for a significant time at ballast displacement. In this light condition, the transom may be out of the water. Also, these hulls are designed with "V" shaped transoms, with transom deadrise angles varying from 19 degrees (AOE), to 21 degrees (TAO), through 25 degrees (AO). These higher transom deadrise angles are considered not as suitable for stern flaps. Nevertheless, because of the attractiveness of stern flaps as a retrofit device, design efforts and model tests to define stern flap performance on the TAO 187 and the AOE 6 are recommended. Research into stern flaps on these hulls, in conjunction with the model test evaluation of other energy enhancement devices, may prove especially promising.

Stator Upstream of Propeller:

The major motivation for the U.S. Navy's interest in this device has been to obtain enhanced powering and enhanced propeller cavitation characteristics. U.S. Navy stator models tested to date, with the exception of a single AE 36 model test, have been mostly on single screw frigate type hullforms. These tests have shown, at Froude scale model test speeds, some minimal powering performance enhancement on the order of 2%. Traditional self propulsion model tests with stators encounter low Reynolds numbers (R_n) on the stator vanes. This is because of the low inflow velocity due to the fixed (as opposed to rotating) stators, the relatively low Froude scaled model test speeds, and the short chord lengths on the stator vanes. The powering improvement at full scale is expected to be better than at model scale. Some special model tests have shown that as R_n is increased, the efficiency increases, thus tending to confirm the hypothesis that the performance with vanes is better at ship scale than at model scale. It is possible that some additional performance improvements (powering reductions) could be obtained from new stator designs oriented more towards energy enhancement. Furthermore, specially designed model experiments in the new Large Cavitation Channel (LCC), might circumvent the low model R_n problem.

Stators have been retrofitted on commercial ships, mostly on ships with fuller afterbodies than the afterbodies typical of Navy ships

Stator retrofit would fall into the "high cost" device category, and are most attractive economically on the destroyers and cruisers. However, for these ships, signature considerations could override energy enhancement considerations for the retrofit. In addition, for these high speed (approximate 30 knot) ships,

and for the 30 knot AOE, there is an elevated risk level with regard to cavitation, hydrodynamic loads, and design development costs. These additional risk factors are difficult to quantify. Due to lack of U.S. Navy full scale experience with retrofit for this concept, it would be more prudent to consider retrofit for slower ships. However, the payback potential as shown in Figure A8, is much less for these slower ships. The most promising candidates would be the LHA / LHD and the TAO Classes.

Main Strut Barrel Designs:

It is doubtful that the retrofit of a new strut barrel design would be cost beneficial. The main emphasis of this concept is to provide better inflow wake into the propeller, for reduced blade root cavitation and increased cavitation inception speeds. While the potential for small powering reductions exists, it is felt that the potential for energy reduction would not offset the substantial cost of retrofit. Empirical and CFD work on this concept is in its preliminary stage. Consideration should be given to follow on model test work, to verify computational predictions, and to determine energy reduction possibilities for new designs.

New Propeller Design, Low RPM / Large Diameter Propeller,
Energy Efficient Tip Propeller:

The concept of a new, more efficient propeller design, is a universal way of reducing powering requirements. Advances in design procedures, and the opportunity to redesign a propeller with the benefit of full scale data, virtually assure that some improvements could be achieved, Bailar and Jessup (8). Previous propeller design studies (on ships that are now mostly retired or at the end of their service lives) concluded at that time that several classes would benefit from new propeller designs, Lindenmuth (9). However, a new propeller for a U.S. Navy vessel is associated with considerable design, R&D, construction, and installation costs. They would definitely be in the "high cost" category of retrofit devices. Thus, in order to economically justify a propeller replacement, a very large improvement in propeller performance must be demonstrated. Such gains can only be obtained for situations where the current propeller performance is very poor.

The propeller efficiency for 10 of the 11 selected candidate ship classes is plotted as a function of propeller thrust loading, as shown on Figure 3. Again, the three spots shown for each ship are, near maximum speed, a representative mid-speed, and the lowest speed of interest. In addition, the ideal efficiency, η_I, based on momentum theory, is also shown on Figure 3, as a dotted line. In making comparisons among the ship propellers, it is important to realize that the DDG, DD, CG, FFG and AOE propellers have a much more severe (30 knot plus) operating environment than the rest of the ships, which have maximum speeds in the 22 to 25 knot range.

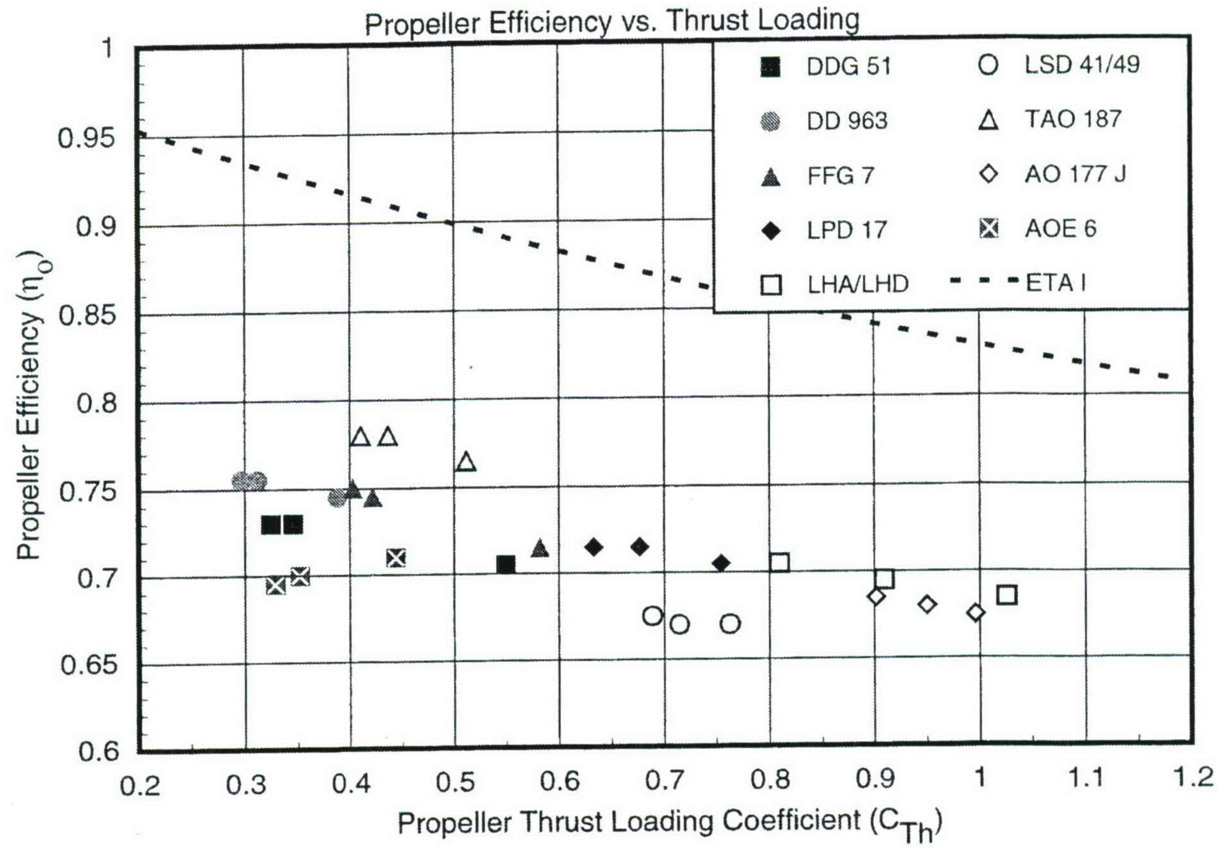

Figure 3. Propeller efficiency for selected U.S. Navy hullforms

• <u>LSD 41/49 Propeller:</u> In the amphibious and auxiliary ships group, the LSD 41/49 propeller efficiency is about 6% worse than the Navy's recent LPD 17 propeller design. The LSD propeller is controllable pitch versus fixed pitch for the LPD, with a blade area ratio about 12 % greater on the LSD propeller. These differences may explain a small part of the 6% performance difference. New propeller retrofit is attractive from a hydrodynamic point of view on these classes, in that a 5 % energy saving is almost certain. Only new propeller blades would be needed for retrofit into the existing hubs. In this way, the retrofit cost could be maintained between the low and medium cost categories, and there would be a possibility for payback in approximately 5 years, (See Figure A6).

• <u>AOE 6 Propeller:</u> In comparison to DDG 51, DD 963, or FFG 7, the AOE 6 has lower propeller efficiency. This may be partly explained by the worse inflow conditions to the AOE propeller, and by ballast condition design constraints applied to the AOE propeller design. In addition, the AOE model propeller cavitation evaluation did not have the benefit of testing at the Large Cavitation Channel (LCC), as did the DDG 51. Recent propeller viewing trials on the AOE showed that the propeller had very good cavitation characteristics, in terms of minimal extent of cavitation over the blade. In the design of such a propeller, good cavitation performance is sometimes obtained through blade shaping and circulation

distribution, which can sacrifice some powering performance. It is possible that with advanced blade sections, and the latest evaluation methods, the efficiency could be improved somewhat. Comparison to the TAO is not recommended because of the lower maximum speed of the TAO.

• Low RPM / Large Diameter Propeller: The concept of using lower RPM, and larger diameter, as a means of achieving a more efficient propeller, is proven technology. However, this is only suitable for retrofit if there is sufficient propeller tip clearance for a larger propeller. No selected ship classes have adequate clearance if current US Navy practices for minimum tip clearances are maintained. Also, in the cases where the ship propulsion machinery has an excess torque capability, or if the ship is to receive a new engine design, the large diameter propeller is possible. None of the selected candidate ships meet this condition. This is not a recommended retrofit option.

• Energy Efficient Tip Propeller: Energy efficient tip propellers present a viable means of getting more efficiency out of a propeller. The efficiency enhancement is due to the an increased tip loading in a way that avoids harmful cavitation or pressure pulses. The U.S. Navy recent approach to this kind of propeller was to incorporate a smooth twist into the tip, as shown on Figure B29a, for the recently designed PC 1 propeller. This design showed good powering and noise characteristics on recent ship trials. Another approach, with a more prominent bend in the tip, is shown in Figure B29b. Both of these approaches represent refinements to existing design procedures. These approaches could be used on the LSD 41/49 propellers as discussed previously.

A more radical approach, to increasing tip loading, is the use of end plates. The concentrated tip loaded (CLT) type propellers with large end plates, (Figures B29c and B29d), have been fitted to more than 120 commercial ships, in both fixed pitch and controllable pitch versions. CLT is a proprietary trade name by one manufacturer. These propellers are claimed to reduce fuel consumption by 8 to 12 percent. Independent verification of these claims is very difficult. However, the claims are believable if subjected to certain considerations, such as, if the original propeller was: too small, very highly loaded, a poor performer in terms of efficiency, or a poor match to the engine in terms of RPM. The end plates clearly incur additional viscous losses. For these propellers to have improved efficiency, these viscous losses must be overcome by a more efficient lift distribution on the blade, or by the ability to carry additional load at the blade tips. The hydrodynamic mechanism for improving efficiency with these end plates favors highly or very highly loaded propellers. Most U.S. Navy ships tend to have propeller loading in the low to moderate range, with the possible exception of some tugs or ships that have a large towing requirement. The suitability of propeller designs with end plates to the high speed combatant hullforms is uncertain because of

propeller cavitation issues. There is, however, one commercial retrofit of this type propeller on a high speed hydrofoil ferry.

Design theories for propellers with end plates have been developed by Andersen (10), and by DeJong (11). Some model tests have shown a 3% increase in efficiency. The details of these design approaches are not fully revealed, however, all approaches present difficulties with cavitation at the blade / end plate juncture. Some investigators also claim that low R_n model tests do not fully simulate the performance gains achievable at full scale. Confirmation of a 3% efficiency gain for the end plate blade tip design for a Naval auxiliary could have a major impact on future propeller design and on the future fuel usage of Navy ships. Therefore, the following research program is recommended:

- In order to minimize the cavitation problem, select a medium speed ship such as LSD 41 or one of the designs that were fully developed & model tested in the Sealift Technology Development Program.
- Develop a propeller design with end plate blade tips, and one for the best equivalent propeller design without end plate blade tip design.
- Conduct high speed, high Reynolds number open water tests on the designs
- Conduct cavitation evaluation and tip flow mapping
- Conduct model powering experiments to determine hull-propulsor interaction.

•<u>End Plates for LSD 41 Propeller:</u> The LSD 41 propellers have been identified as a design for which performance could be improved by as much as 6%, using the latest conventional propeller design methods. Because of the high cost of new propeller blades, the payback period for a new propeller blade refit is long, about 5 years. The U.S. Navy has experience with the retrofit of numerically cut tip fairings on surface ship propellers. The propeller modification cost, of fitting end plates, may be on the order of 2/3 the cost of making new blades. This, of course, would reduce the cost of retrofit. However, without actually performing some design and model test work, it is difficult to estimate the performance improvement due to end plates.

<u>Fairwaters, Hub Fins, Rudder modifications:</u>

These devices are grouped together because they have the following common characteristics: (1) They are all low to medium cost retrofit devices, and (2) their effectiveness is highly dependent on the local flow conditions

• <u>Propeller Fairwater Designs</u>: This energy reduction concept is applicable mostly to controllable pitch propellers. These can benefit most because of the relatively large propeller hub diameter, and consequently relatively large base drag of the hub without fairwater or with a poor fairwater design. The DDG 51, CG 47 / DD 963/993, FFG 7, LSD 41&49, and TAO 187 class ships have controllable pitch propellers. All, except the TAO, have a "button" shaped fairwater. This "button" shape is characterized by a rapid curvature

immediately aft of the hub. It is believed that this rapid curvature contributes to excessive base drag. Carefully conducted self propulsion model tests of various fairwater designs for the DD-963 destroyer showed a 1.0 % reduction in delivered power for a truncated cone design relative to the "button" shaped design, Lin and Borda (12). The TAO 187 fairwater is a stepped down design with no hydrodynamic fairing, and it is believed that an improvement is very likely with a new faired design. Even with only a modest 1% energy improvement, these concepts are attractive due to ease of ship integration and expected low installation and R&D costs. However, because of the small energy improvement, it is recommended that the fairwater concept be considered as a "piggy back" to other energy enhancement concepts, in order to share the costs of model tests, dry docking, retrofits, and ship trials.

• Hub Fins: The purpose of putting blades on the propeller hub/fairwater is to enhance propeller performance by making use of the fluid energy near the propeller blade root area. See Figure B33 for a photograph of a comparative commercial device. The extent of the energy enhancement will be significantly affected by the adequacy or limitations of the original propeller design, especially with regard to the hydrodynamics in the root area. State of the art commercial propeller design practice is to attempt to take into account hub effects, however, lack of good knowledge about local flow into the root-hub intersection hinders these efforts. The more traditional commercial practice is to slightly modify an existing Troost series propeller. For current U.S. Navy combatant ship propellers, root cavitation considerations play an important role in the hydrodynamic design of the root area. The goal is to avoid cavitation on both sides of the propeller blade near the root, which can result in some inherent kinetic energy loss. The very latest design methods, which are still in the research stage, attempt to account more completely for hydrodynamic propeller blade root and hub interactions. In addition, the design of the propeller blade root is often significantly affected by propeller strength considerations. This leads to increased root thickness or filleting, and on controllable pitch propellers, the root chord is limited by the rotating blade palm diameter. Thus, even well designed propellers can experience losses associated with the flow in the root area of the propeller blade.

The open water propeller efficiency shown in Figure 3 is not a good indicator of which propeller would benefit from these hub fins. The open water propeller efficiency reflects the overall performance of the propeller blades only, i.e. without the hub. During the open water model test, the propeller is powered by a downstream shaft, and, in addition, thrust and torque tare loads of the hub spinning alone (without the blades) are subtracted out.

The hub-fin units are commercially available, with over 200 such devices having been applied to variety of commercial ships. Claimed savings in fuel consumption is 3 to 5 percent. These savings are believable,

especially if the original propeller was in some way deficient. However, there is no direct U.S. Navy verification of these claims. The concept is recommended for retrofit, due to its expected low associated costs of ship integration and installation. The recommendation is to explore retrofit on a selected auxiliary ship prior to conducting R&D into suitability for eventual retrofit on a combatant. The combatant ship retrofit involves much more extensive design and model test work because of the cavitation and signature related potential impacts of such a device.

• Rudder Modifications: Examples of possible rudder modifications are the thrusting fin, and the rudder bulb fin, as shown in Figure B21. In addition, there is a split rudder concept that aligns the upper (above the propeller centerline) and lower portion of the rudder at slightly different angles. These devices work when there is a strong vertical or horizontal flow component in way of the device. Under such conditions, the devices can either produce thrust, or decrease rotational energy losses, or both. The flow angularity is usually the result (or combination) of the propeller slipstream, the bilge vortex, and the hull wake. The thrusting fin, and rudder bulb fin, have been fitted mostly to single screw commercial ships. Powering reductions up to 5% have been reported. U.S. Navy model tests have shown a 3% powering reduction for a thrusting fin, and a 1% powering reduction with a split rudder. In general, the devices have mostly been applied to single screw ships, but will work with twin screw if strong angular flow conditions are present.

The recommendation with regard to the alternative fairwater designs, hub fins, rudder bulbs, and twisted rudder devices, is to perform brief flow visualization model tests and brief propeller hub flow calculations, for all of the selected ship classes. CDNSWC has all of the nine hull models and design propeller models, and, in addition, the propeller design geometry is readily available. The following work is envisioned:

- Underwater flow visualization to determine flow directions on the rudder to help with the selection of the most suitable hull for thrusting fins, and for the split rudder.
- Stroboscopic underwater flow visualization on the propeller hubs to help with the selection of the most suitable candidate for alternative fairwaters, and hub fins.
- Simple vorticity measurement downstream of the propeller to help with selection of ships for hub fins.
- Simple calculations of flow over the propeller blade near the root area to identify the best candidate for hub fins.

The hull geometry and operational characteristics of the selected hulls tend to favor some of the above retrofit concepts. The AO 177 is the only single screw merchant ship type hullform, and from a geometry point of view, it is the only realistic candidate for a rudder bulb. The ships with controllable pitch propellers are the only realistic candidates for alternative fairwaters. Thrusting fins will impose some additional loads on the rudders of all the ships, and calculations will be needed to determine if the additional load is critical or not. On ships with horn rudders such as the TAO 187 and LPD 17 there is a possibility for locating the thrusting fins on the fixed part of the horn, and thus minimize any impact on the rudder. On the high speed

ships such as DDG 51, DD 963, CG 47, FFG 7, and AOE 6, the design complexity and possible retrofit cost, of any of these devices, is increased because of cavitation considerations.

• Propeller Pitch Scheduling: Propeller pitch scheduling is an at-sea practice, rather than a retrofittable hydrodynamic device, of setting and maintaining the optimal propeller pitch for minimal engine fuel consumption. It is highly recommended for study and eventual adoption on all ships which employ controllable-pitch propellers for their main propulsion. These ships are: DDG 51, CG 47 / DD 963/993, FFG 7, LSD 41&49, TAO 187, and possibly the new LPD 17 Class.

The traditional view of propeller pitch scheduling involves a set of instructions to the ship's force on setting propeller pitch. The U.S. Navy conducted full scale trials on the *USS Spruance* (DD 963) to evaluate the effects of pitch scheduling during trailed shaft operations, Hansen and Santelli (13). Analysis of the trials data revealed that a fuel savings of 1 to 2 percent could be achieved in the portion of the speed range between 15 to 20 knots. Implementation of propeller pitch scheduling was envisioned to be a manual process, performed by the ship's crew, according to specific instructions.

One of the difficulties with this traditional approach is that the propeller pitch indicator (on board the ship) is often in significant error. Propeller pitch is set by hydraulic pressure exerting force on a servo mechanism. Many factors may affect the accuracy of the set propeller pitch, such as: hydraulic fluid temperature, thermal expansion of long pitch control rods, propulsion shaft compression, wear on the system, and the accuracy of the pitch indicator itself. For ship trials the pitch indicator can be calibrated in drydock, pierside by divers, underway at speed, or by a combination of techniques, Klitsch et. al. (14). The only pitch point known for sure, is an over-pitched position that is up against mechanical stops. This pitch problem has been known for some time, and for DDG 51, an in-hub pitch sensor was developed,. However, this system failed, and was removed from the ship. The development of reliable and accurate pitch indicators is strongly recommended.

Another approach to pitch scheduling, is to purchase or develop a real time feedback system. This system would automatically optimize the combination of propeller pitch and engine RPM, for minimum fuel consumption. A survey should be conducted to determine what commercial systems are available today, and to see if they are adequate for U.S. Navy use. Actual sensing of the propeller pitch may not be critical to the system. The principal of optimization would be to minimize fuel flow at an operator specified ship speed, by varying propeller pitch and thus engine RPM. Both software algorithms, and accurate hardware such as thrust and torque meters, fuel flow meters, wind indicators, and ship motion sensors, might be needed for such a system. Such a system could be readily adapted to other desirable modes of operation, including optimization for minimum propeller noise, maximum ship speed, and maximum acceleration. The

real-time nature of the system would automatically account for the effects of hull and propeller fouling, and the normal wear related degradation of engine performance.

The sensitivity of delivered power to propeller pitch variations will vary from ship to ship. For the LSD 41, the sensitivity of delivered power and propeller RPM was calculated for a ship speed of 22 knots, Bell (15). The results for LSD 41, relative to the nominal design pitch condition, were:

6% reduction in pitch caused a 3.5% RPM increase and a 2.2% delivered power increase

6% increase in pitch caused a 3.5% RPM reduction and a 0.7% delivered power reduction

The change in fuel consumption was not computed, nevertheless, since this is a diesel powered ship, the fuel consumption change is expected to be on the same order as the powering change. The magnitude of the fuel usage improvement, due to ensuring operations at optimal pitch, represents only a small gain per ship. However, the overall U.S. Navy fleet savings could be expected to be significant, due to the gains on a large potential number of ships. The total savings could be calculated for assumed pitch variations.

The expected low implementation costs and widespread potential application for pitch scheduling, both the traditional and the automatic real time methods, make this a highly desirable option. The fuel savings is difficult to quantify. The baseline performance depends on the current skill of the ship's crew in selecting pitch and engine RPM for a given speed, and this skill could vary from ship to ship.

GENERAL LISTING OF SUBJECT REFERENCES

Within Appendix C is provided a general listing of the compiled references pertaining to the subject of energy enhancing concepts and devices. References listed are in open literature. Many of these references were utilized in the composition of this report and are referred to within the main text and/or the text of the appendices. All of these references are available from CARDEROCKDIV, NSWC Code 5200.

CONCLUSIONS

Information was compiled on U.S. Navy surface ship classes. This data was utilized to select eleven (11) candidate classes for the possible retrofit of energy savings devices. The criteria for this selection was those ship classes that had the highest potential life-cycle fuel savings with the installation of an energy savings device. The annual potential fuel cost savings and potential life cycle fuel savings, attributed to the installation of a hypothetical 5% energy savings device, was then determined for each of the identified candidate ship classes.

Descriptions are provided of many energy enhancing concepts and devices, including depiction of the geometry, principles of operation, practical considerations, full scale or model scale experiences, and energy reduction potential. Fourteen (14) devices were selected for potential retrofit to U.S. Navy surface ships.

The criteria for this selection included applicability to U.S. Navy type hullforms, suitability for retrofit, reliability, and history of demonstrated energy enhancement potential.

An evaluation was then made in regard to which of the fourteen selected energy enhancement devices are to be recommended for consideration as cost beneficial for retrofit on the eleven identified candidate U.S. Navy surface ship classes. Many practical considerations beyond suitability, such as cost (R&D, ship integration, manufacturing, and installation), availability of devices with greater potential, technical risks, etc., were taken into account for each hullform.

RECOMMENDATIONS

(1) Continue the retrofit bulbous bow research and development work already planed for the DDG 51. Continue the ongoing stern flap work for the DDG 51 Class and for the DD 963 / CG 47 ship classes. A stern flap for the FFG 7 class has already been developed. The fuel consumption of the DD 963 / CG 47 ship classes and the FFG 7 class can benefit from retrofit bulbous bows, however, major research and development efforts for these ships should be performed after the results from the DDG 51 bulbous bow program are analyzed.

(2) Hydrodynamic research and development work to design retrofit energy enhancement devices for the TAO 187 Class is recommended. The following retrofit items, listed in order of priority, should be considered:

- Bow bulb (traditional type and the new small near surface type)
- New fairwaters and/or fairwater fins
- Thrusting fins on the rudders
- Stern end bulb and/or stern flap

(3) Brief model flow visualization experiments and propeller hub flow computations should be conducted on the models that represent the 11 ship classes identified in this report. These experiments would determine which of these ships possess favorable hydrodynamic characteristics for the retrofit of fairwater fins, new fairwaters, thrusting fins on the rudder, and modified rudders. These retrofit devices are all very attractive because of their low cost and ease of retrofit.

(4) A system that automatically selects an optimum propeller pitch and engine RPM combination for minimized fuel usage could be applied to seven major ship classes with controllable pitch propellers (consisting of 175 ships in total). The potential fuel saving benefits of such a system should be estimated using current ship usage patterns, engine characteristics, and powering characteristics. The availability, applicability, and accuracy of off-the shelf commercial systems should be determined. If there are no satisfactory commercial systems, then the U.S. Navy should embark on the development of

such a system. In addition to energy enhancement, such a system could have alternative modes of operation for minimizing propulsor noise or for maximizing propeller thrust.

(5) An investigation into the potential benefits and design methodologies for stern end bulbs should be started. For destroyer / cruiser type ships, with conventional low deadrise submerged transoms, the performance of a stern bulb alone, and in combination with a stern flap, should be investigated. In addition, the possibility of using a stern end bulb as a housing for the underwater deployment / retrieval of various towed array sonar arrays should be investigated, for both retrofit and new design concepts. For the auxiliary type ships such as AOE 6, TAO 187, and AO 177 classes, the stern end bulb performance should be investigated for both the design and ballast displacement.

(6) The development of a bulbous bow design oriented towards retrofit on the LHA class is recommended. New developments in bulbous bow design, which could be adapted to the LHA, may make a retrofit an attractive option.

(7) The development of a stern flap on the LSD class and the LHA / LHD class is recommended. On the LSD the flap should be effective for speeds of roughly 16 knots and above. On the LHD the flap should become effective at speeds of roughly 18 knots and above. The flap design has to be optimized for the mission operational speed profile of the ship. Stern flap design needs to consider amphibious operations and stern gate deployment. The low deadrise transom shape on these ships is suitable for stern flaps.

(8) Research on energy efficient tip propellers should be pursued. The general performance claims for propellers with end plates should be verified through design and high Reynolds number model tests. If a theoretical 3% efficiency improvement claim is valid for U.S. Naval ships, there could be a great impact on the fuel consumption of new ships if fitted with this type of propeller. The LSD 41 propellers have been identified as a design less efficient than possible with today's state of the art propellers. From a retrofit cost point of view, hydrodynamic design efforts and feasibility analysis of retrofitting end plates to the current LSD propellers is recommended.

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15. This reference is not in the public domain.

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APPENDIX A:

U.S. NAVY SURFACE FLEET OVERVIEW

Presented in Appendix A is the overview information collected on the existing US Navy fleet of surface ships. Within this appendix, the US Navy surface ship fleet is separated into five main surface force classifications. The five main ship force classifications of this appendix do not correspond with the official US Navy List of Ship Classifications, updated periodically [1]. These five ship force classifications are: (A) Surface Combatants, (B) Amphibious Warfare Ships, (C) Fleet Auxiliary Force, (D) Mine Warfare, and (E) Active Strategic Sealift. Ships or ship classes in each of the main ship functional force classifications are further subdivided into nineteen (19) categories separated by ship type (ship function). The individual US Navy ship class overview information is presented on only those classes for which activity status[2] data indicates that at least one ship remains active in the fleet. Eliminated from the overview are those classes for which all ship's activity status is listed as non-deployed (or non-deployable), out of service, inactive, inactive status in Military Sealift Command (MSC), assigned to Naval Reserve Force (NRF), or sold to foreign navies, etc. In some instances, two ship classes, listed separately in the US Navy ship register, were grouped together in the present overview. These specific instances, indicated in the present overview, occur when the same underwater hull design was utilized for the two classes. For the purpose of this energy study, the hull design was the primary differentiating factor. The present US Navy class overview resulted in the identification of nearly sixty (60) active ship classes.

The individual US Navy ship class overview information includes data such as number of ships, activity status, number of ships planned or being presently built, and remaining service life, as well as common data on ship type, size (displacement, length, beam, draft), speed, range, and propulsion (number of shafts, installed power, prime mover). The data comprising the US Navy surface fleet overview was extracted from the following sources: The first source being a variety of different types of documents within the technical library at CARDEROCKDIV,NSWC, Carderock site. The second source was the Polmar reference guide book of the U.S. Fleet (Ref. A1)[3]. This book was the source for much of the activity status of the older ship classes, as well as additional fleet information. A third source was the broadly known book of world-wide fighting forces, published by Jane's (Ref. A2). This was again a source of additional fleet information. This overview of US Navy ship classes, compiled for this energy study, is presented in the following Table A1.

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[1] The official US Navy List of Ship Classifications includes a much more extensive differentiation between ship force functions, and consequently includes many additional ship classification branches.

[2] US Navy surface ship fleet present activity status is presented when available, however, many of the older ship classes reflect activity status as of FY94.

[3] Reference for Appendix A are presented on the last page of the appendix.

Table A1. Overview of present U.S. Navy ship classes

SHIP TYPE	CLASS	Number (plan)	HULL identifications	Commision Dates first-last of Class	EST average class service life left, yrs	DISPLACEMENT tons	LENGTH, lbp (loa), ft	Beam (max) ft	Draft, ft Nav (hull)
SURFACE COMBATANTS									
CARRIERS	Forrestal	4	AVT 59, CV 60-62	1956 - 1959	4	80660 - 81500	990 (1052)	130	37
	Kitty Hawk&JFK	4	CV 63,64,66,67	1961 - 1968	8	79720 - 85490	990 (1046)	130	37.5
	Enterprise	1	CVN 65	1961	6	93970	1040 (1101)	133	39
	Nimitz	7 (2)	CVN 68-76	1975 - present	32	91490-102000	1040 (1092)	134	37 - 38.5
CRUISERS	Ticonderoga	27	CG 47-73	1983 - 1994	29	9620 - 10130	532 (567)	55	31.5
	Bainbridge&Leahy	10	CG 16-24, CGN 25	1962 - 1964	0	8200 - 8590	(565).	58	31.5
	California	2	CGN 36, 37	1974 - 1975	15	10530	(596).	61	31.5
	Virginia	4	CGN 38 - 41	1976 - 1982	19	11300	(585).	63	31.5
	Belknap&Truxtun	10	CG 26-34, CGN 35	1964 - 1967	0	8065 - 9127	(547).	55	29
	Long Beach	1	CGN 9	1961	0	17525	(721).	73	31
DESTROYERS	Spruance & Kidd	35	DD 963-997	1975 - 1983	18	8320 - 9874	530 (563)	55	29 (19)
	Burke, Flts I,II,IIA	13 (37)	DDG 51-	1991 - planned	35	8500 - 9220	466 (505)	67	32.7 (20.7)
FRIGATES	Oliver Haz Perry	51	FFG 7 ~ 61	1977 - 1989	24	3660 - 4100	415 (445-455)	45	24.5 (14.8)
	Knox	40	FF 1052-1097	1969 - 1974	15	4260	415 (440)	47	25
PATROL	Cyclone	13	PC 1-13	1994 - present	35	341	160 (170)	25	7.9
AMPHIBIOUS WARFARE SHIPS									
Command	Blue Ridge	2	LCC 19-20	1969 - 1970	10	18650	580 (637)	82 (108)	29
Assault	San Antonio	(12).	LPD 17-28	1998-2008 plan	35	24800	656 (684)	98	23
	Wasp	6	LHD 1-6	1988 - present	33	40530	778 (844)	106 (140)	26.6
	Tarawa	5	LHA 1-5	1976 - 1980	18	39970	778 (834)	106 (132)	26
	Iwo Jima	7	LPH 2, 3, 7, 9-12	1961 - 1970	7	18800	556 (602)	84 (104)	26
Transport/Cargo	Austin	11	LPD 4-9,10,12-15	1965 - 1971	8	16590 - 18800	(570).	84 (100)	24
	Anchorage	5	LSD 36-40	1969 -1972	11	13700 - 14000	534 (553)	85	20
	Whidbey Island	9 (3)	LSD 41-48, 49-52	1985 - present	30	17745	580 (610)	84	20
Tank Landing	Newport	3	LST 1179-1198	1969 - 1972	11	8450	522 (561)	70	6fwd, 17aft

Table A1. Overview of present U.S. Navy ship classes (continued)

SHIP TYPE	CLASS	Number (plan)	HULL identifications	Commision Dates first-last of Class	EST average class service life left, yrs	DISPLACEMENT tons	LENGTH, lbp (loa), ft	Beam (max) ft	Draft, ft Nav (hull)
FLEET AUXILIARY FORCE									
Command	Raleigh	3	AGF 1-3	1962 - 1964	6	14865.	500 (521)	84	22
	Austin	12	AGF 4-15	1965 - 1971	10	16590	(569).	84	24
Tenders	Gompers	6	AD 37,38	1967 - 1968	8	20500	(644).	85	23
	Yellowstone	4	AD 41-44	1980 - 1983	22	20500	(644).	85	23
	Spear&Land	6	AS 36-41	1970 - 1981	17	22600 - 23500	(646).	85	24 or 29
	Lake&Hunley	4	AS 33,34	1964 - 1965	4	21090	(644).	85	29.5
Stores/Support	Mars	10	AFS 4, TAFS 1-10	1963 - 1970	8	16070	530 (580)	79	24
	Kilauea	8	AE 26-29, 32-35	1968 - 1972	11	19940	(564).	81	28
	Suribachi/Nitro	5	AE 21-25	1956 - 1959	0	17450	(512).	72	29
	Supply	2 (2)	AOE 6-8, 10	1994 - present	35	48800	(754).	107	38
	Sacramento	4	AOE 1-4	1964 - 1970	8	51400 - 53600	(793).	107	39
Oilers	Henry J Kaiser	16	TAO 187-204	1986 - 1994	31	40700	650 (678)	98	36
	Cimarron (Jumbo)	10	AO 177-186	1981 - 1983	22	37870	(708).	88	35
	Wichita	4	AOR 4-7	1970 - 1976	13	41350	(569).	96	33
Ocean Surveillance	Stalwart	18	TAGOS 1-18	1984 - 1990	27	2290	203 (224)	43	15
	Victorious SWATH	5	TAGOS 19-23	1991 - present	33	3440	190 (235)	94	25
Salvage	Safeguard	4	ARS 50-53	1985 - 1986	26	3190	240 (254)	51	15.5
	Edenton	3	ATS 1-3	1971 - 1972	12	3220	264 (288)	50	15
Fleet Ocean Tugs	Powhatan	7	TATF 166-172	1979 - 1981	20	2260	226 (240)	42	15
MINE WARFARE									
Countermeasures	Avenger	14	MCM 1-13	1987 - 1994	31	1312	213 (224)	39	11
	Osprey	12	MHC 51-62	1993 - present	35	895	174 (188)	36	9.5
ACTIVE STRATEGIC SEALIFT									
Cargo/Freighters	J P Bobo	5	TAK 3008-3012	1985 - 1986	25	44330	(675).	106	30
	Sgt M Kocak	3	TAK 3005-3007	1981 - 1983	22	48750	(821).	106	32
	Cpl L J Hauge	5	TAK 3000-3004	1979 - 1980	19	46550	(755).	90	37
	-	2	TAK 2049,2064	1975 - 1975	15	62315	(894).	100	60
	-	2	TAK 322,323	1978	18	40360	(670).	87	35
	-	1	TAKF 2062	1974	14	69555	(738).	135	35
	-	1	TAKB 924	1969	9	66630	(857).	106	40
	-	1	TAKR 9205	1984	24	31390	(512).	105	30
Oilers	-	1	TAOT 181	1957	0	34700	(615).	85	34
	-	1	TAOT 5075	1958	0	44840	(661).	90	36

Table A1. Overview of present U.S. Navy ship classes (continued)

CLASS	Installed Power hP	Number Shafts	Speed kts	Range, n. miles at speed, kts	Class Assignment/Activity	Powerplant (Prime Mover)
SURFACE COMBATANTS						
Forrestal	260,000	4	34	12000 @ 20	3 active, 1 (AVT69, non-deployed)	8 Babcock&Wilcox Boilers, 4 (GE or Wsthus) steam turbines
Kitty Hawk&JFK	280,000	4	30+	12000 @ 20	3 active, in yard (modernization)	8 Foster Wheeler Boilers, 4 Westinghouse Turbines
Enterprise	280,000	4	30+	NA	overhaul in yard	Nuclear: 2 (Wsthus) PWR A4W. 4 (GE) steam turbines
Nimitz	280,000	4	30+	NA	7 active, 2 building	Nuclear: 8 (Wsthus) PWR A2W. 4 (Wsthus) steam turbines
Ticonderoga	80,000	2	30+	6000 @ 20	27 active	4 gas turbines (GE LM2500)
Bainbridge&Leahy	70,000	2	30+	8000 @ 20	Inactive, Leahy is nuclear	4 Babcock&Wilcox Boilers, 2 steam turbines (GE or DeLeval)
California	70,000	2	30+	NA	2 active	Nuclear: 2 (GE) PWR D2G, 2 steam turbines
Virginia	70,000	2	30+	NA	4 active	Nuclear: 2 (GE) PWR D2G, 2 steam turbines
Belknap&Truxtun	85,000	2	33	7100 @ 20	reserved or sold	4 Babcock&Wilcox Boilers, 2 steam turbines (GE or DeLeval)
Long Beach	80,000	2	30.5	NA	out of service	Nuclear: 2 (Wsthus) PWR C1W, 4 steam turbines (GE)
Spruance & Kidd	86,000	2	33	6000 @ 20	35 active	4 gas turbines (GE LM2500)
Burke, Flts I,II,IIA	100,000	2	32	4400 @ 20	13 active, 37 planned	4 gas turbines (GE LM2500-30)
Oliver Haz Perry	40,000	1	29	4500 @ 20	35 active, 16 Naval Res or sold	2 gas turbines (GE LM2500)
Knox	35,000	1	27	4300 @ 20	8 NRF, all others Res or sold	2 Babcock&Wilcox Boilers
Cyclone	14400	4	36	2000	13 active	4 Diesels Paxman 16RP200M
AMPHIBIOUS WARFARE SHIPS						
Blue Ridge	22,000	1	22	13500 @ 16	2 active	2 Foster Wheeler Boilers, 1 (GE) steam turbine
San Antonio	40,000	2	23		12 planned	4 diesels
Wasp	70,000	2	24	9500 @ 20	4 active, 2 building	2 Combustion Engr Boilers, 2 (Wsthus) steam turbines
Tarawa	70,000	2	24	10000 @ 20	5 active	2 Combustion Engr Boilers, 2 (Wsthus) steam turbines
Iwo Jima	23,000	1	23	10000 @ 20	4 active, possibly all 7 active	2 Combustion Engr Boilers, 1 (Wsthus) steam turbine
Austin	24,000	2	21	7700 @ 20	11 active	2 Foster Wheeler Boilers, 2 (DeLaval) steam turbines
Anchorage	24,000	2	22	14800 @ 12	5 active	2 Foster Wheeler Boilers, 2 (DeLaval) steam turbines
Whidbey Island	41,000	2	22	8000 @ 20	9 active, 3 building	4 diesels SEMT pielstick 16PC2.5
Newport	16,500	2	22	2500 @ 14	3-15 active, remainder NRF or AR	6 diesels (GM 16-645-E5)

Table A1. Overview of present U.S. Navy ship classes (continued)

CLASS	Installed Power hP	Number Shafts	Speed kts	Range, n. miles at speed, kts	Class Assignment/Activity	Powerplant (Prime Mover)
FLEET AUXILIARY FORCE						
Raleigh	24,000	2	21.5	9600 @ 16	only 1 active	2 Babcock&Wilcox Boilers, 2 (DeLaval) steam turbines
Austin	24,000	2	21	7700 @ 20	only 1 active	2 Foster Wheeler Boilers, 2 (DeLaval) steam turbines
Gompers	20,000	1	20	?	2 active	2 Combustion Engr Boilers, 1 (DeLaval) steam turbine
Yellowstone	20,000	1	20	?	3 active	2 Combustion Engr Boilers, 1 (DeLaval) steam turbine
Spear&Land	20,000	1	20	10000 @ 12	5 active	2 Foster Wheeler Boilers, 1 (GE) steam turbine
Lake&Hunley	20,000	1	20	7600 @ 18	3 active	2 Combustion Engr Boilers, 1 (DeLaval) steam turbine
Mars	22,000	1	21	10000 @ 20	9 active	3 Babcock&Wilcox Boilers, (DeLaval) steam turbine
Kilauea	22,000	1	22	10000 @ 20	7 active	3 Foster Wheeler Boilers, 1 (GE) steam turbine
Suribachi/Nitro	16,000	1	20.5	10000 @ 20	2 active	2 Combustion Engr Boilers, 1 (Bethlehem) steam turbine
Supply	105,000	2	25	?	2 active, 2 building	4 gas turbines (GE LM2500)
Sacramento	100,000	2	26	10000 @ 17	4 active	4 Combustion Engr Boilers, 2 (GE) steam turbines
Henry J Kaiser	32,540	2	20	6000 @ 20	18 active MSC	2 diesels (Colt-Piel. 10PC4.2V)
Cimarron (Jumbo)	24,000	1	19	?	5 active	2 Combustion Engr Boilers, 1 steam turbine
Wichita	32,000	2	20	1000 @ 16	3 active	2 Foster Wheeler Boilers. 2 (GE) steam turbines
Stalwart	3200	2	11	4000 @ 11	9 active MSC	4 Caterpillar diesel generators, 2 (GE) electric motors
Victorious SWATH	3200	2	16	3000 @ 10	5 active MSC	4 Caterpillar diesel generators, 2 (GE) electric motors
Safeguard	4200	2	13.5	8000 @ 12	4 active	4 (Cat) diesels, Kort-nozzels
Edenton	6000	2	16	10000 @ 13	3 active	4 diesels (Paxman 12 YLCM)
Powhatan	4500	2	15	10000 @ 13	7 active	2 (GM) diesel genertors, electric motors, Kort-nozzels
MINE WARFARE						
Avenger	2280	2	13.5	2500 @ 10	14 active	4 diesels
Osprey	1600	2	12	1500 @ 10	8 active, 4 building	2 diesels, 2 hydraulic-electric motors, Voith-Sch props
ACTIVE STRATEGIC SEALIFT						
J P Bobo	27,000	1	18	13000 @ 18	5 active	2 diesels (Sto-Wrks 16TM410)
Sgt M Kocak	30,000	1	20	13000 @ 20	3 active	2 boilers, 2 (GE) steam turbines
Cpl L J Hauge	16,800	1	17.5	11000 @ 16	5 active	1 diesel (Seltzer 7RND76M)
-	32,000	1	19+	15000 @ 20	2 active	2 Combustion Engr Boilers, 2 (DeLaval) steam turbines
-	20000	?	16	?	2 active	?
-	19,900	1	16	24000 @ 13	1 active	1 diesel
-	20000	?	17	?	1 active	?
-	20000	?	16.5	?	1 active	?
-	20,460	1	18	?	1 active	2 boilers, 2 turbines
-	15,000	1	17	14000 @ 17	1 active	2 Combustion Engr Boilers, 2 (Bethlehem) steam turbines

The data of this US Navy surface fleet overview was utilized to obtain information for identification of candidate ship classes with the highest potential life-cycle fuel consumptions. These ship classes would possess the greatest potential fuel savings benefits by way of installment of energy enhancement devices. Because of the difficulties in obtaining the actual fuel usage data on all of the nearly sixty (60) identified active ship classes, another approach was undertaken. The field of potential high fuel usage ship classes was narrowed down by taking into consideration that class life-cycle fuel consumption rating would be a result of the following three characteristics: number of ships in class, remaining average service life, and installed power of the prime mover. A ship class possessing relatively high values in these three characteristics would, therefore, have a high potential life-cycle fuel consumption. The overview data pertaining to the number of ships in (or planned for) the class, remaining service life, and installed power, is presented in graphical form in Figure A1. The data was then used to determine figure of merit factors to quantify these three characteristics. The first factor, Power*Number, is simply the multiplicative sum of the number of ships in class and the class installed power. The second factor, Power*Number*Life, simply multiplies the Power*Number factor by the average years of remaining service life for the class. These figure of merit factors are presented in bar graph form in Figure A2. The candidate ship classes with the highest potential life-cycle fuel consumptions were identified as those which exhibited a relatively high Power*Number*Life merit factor, (as judged by an elevated bar graph level on Figure A2).

A decision was then made to place an additional criteria on the candidate ship classes. Only those ships which burned fossil fuels would be considered for further analysis. Realistic cost savings, from reduced fossil fuel consumption, could be determined for these candidate classes. Excluded from further consideration in this energy study were those surface ships equipped with nuclear power. Several of these ships did, however, exhibit high values in the figure of merit analysis. There is the possibility, with enhanced hull and/or propulsor performance, of effecting overall life-cycle costs of these ships by extending the service life of the reactor nuclear core. However, assessment of this scenario would be difficult and is not considered at this time.

Eleven US Navy surface ship classes were identified as having high potential life-cycle fuel consumptions. These eleven ship classes, are candidates for retrofit of energy savings devices, and are recommended for further consideration in this energy study. The eleven US Navy surface ship classes include four from classification (A) Surface Combatants, four from classification (B) Amphibious Warfare Ships, and three from classification (C) Fleet Auxiliary Force. No candidate ship classes were identified from either classification (D) Mine Warfare or classification (E) Active Strategic Sealift. The candidate US Navy surface ship classes, identified for further consideration in this energy study, are presented in the following Table A2. Note: the four new classes of sealift ships just being launched are not contained in this overview.

Table A2. US Navy surface ship classes identified as candidates for retrofit of energy enhancement devices

Classification (A) Surface Combatants

Ticonderoga, CG 47
Spruance / Kidd, DD 963 / DD 993
Arleigh Burke, DDG 51
Oliver Hazard Perry, FFG 7

Classification (B) Amphibious Warfare Ships

San Antonio, LPD 17
Wasp, LHD 1
Tarawa, LHA 1
Whidbey Island / Harpers Ferry, LSD 41 / LSD 49

Classification (C) Fleet Auxiliary Force

Henry J Kaiser, TAO 187
Cimarron (Jumbo), AO 177
Supply, AOE 6

The fossil fuel carrier class of Kitty Hawk and John F. Kennedy (CV 63 & CV 67) exhibited a slightly elevated Power*Number*Life merit factor bar graph level on Figure A2. However it was eliminated from contention because it was felt that installation of energy enhancement devices on this class would not be economically justified. This decision was based on the low number of ships in the class (4) and the short average remaining service life (< 10 years). The elevated merit factor was solely based upon the relatively high installed power (280,000 hP).

Obtaining the actual fuel usage data for these identified candidate ship classes was the next step. Information on ship annual fuel usage and fuel rates was obtained from Navy VAMOSC data[4] supplied by the Naval Center for Cost Analysis (NCA). Presented in Table A3, is the US Navy ship average annual fuel consumptions, for the selected candidate classes. As indicated, no fuel usage data was reported for three of the classes, therefore, it was necessary to estimate data for these. The Navy VAMOSC fuel data is separated into both barrels of fuel consumed underway and not underway. Utilized in this energy analysis is only the ship fuel consumption underway. Additionally, it was assumed that only 70 percent of the reported underway fuel consumed was utilized predominantly for ship propulsion. The remaining 30 percent is assumed for ship auxiliary generators, hotel loads, etc. Henceforth, all of the analyses presented, reflect annual propulsion fuel usages equal to 70 percent of the reported Navy VAMOSC underway fuel consumed. The data on individual ship and class averaged annual barrels of fuel used for propulsion, is presented in bar graph form in Figure A3.

In order to determine if an energy saving device makes economic sense in terms of payback on investment, it was assumed that a hypothetical device would save 5 percent on propulsion fuel. To

[4] Navy VAMOSC data supplied by Naval Center for Cost Analysis (NCA) from a report dated 11/21/95, reflecting individual class fuel usages from FY85 through FY94.

make this 5% hypothetical device more realistic, it was also assumed that it could have three possible ranges of cost, low, medium, and high, depicted as follows:

Device Cost Range	Total R&D Cost	Installation Cost / ship	(Example Device)
Low Cost	\$ 500K	\$ 100K	stern flap
Mid Cost	\$ 1M	\$ 500K	bow bulb
High Cost	\$ 2M	\$ 1M	propeller

The simple following constant dollar analyses were then performed to determine the possible fuel cost[5] savings associated with the 5% hypothetical device, on each identified US Navy class:

- Annual potential fuel saved (barrels), and annual potential fuel cost savings ($K), Figure A4.
- Estimated costs of R&D and full scale installation, Figure A5.
- Fuel cost savings potential for short-term (5 years), Figure A6.
- Fuel cost savings potential for mid-term (10 years), Figure A7.
- Total life cycle fuel cost savings potential (remaining class service life), Figure A8.

It is readily apparent that potentially the most significant fuel savings could be realized with the cruisers and destroyers, (Figure A4). If the requirement is to show a net savings, i.e. payback, in a five year short term, than only devices in the low cost and median cost ranges should be considered (Figure A6). For payback in ten years, even the devices in the high cost range look attractive for several of the identified ship classes, (Figure A7). It is interesting to note that over the remaining class service life, the initial cost of the device has only a moderate impact on the net savings, (Figure A8).

[5] For the fuel cost savings, a per barrel fuel cost of $55 was utilized. This value has been recommended by NAVSEA, and reflects the cost of procurement and delivery.

REFERENCES OF APPENDIX A

A1. Polmar, N., The Naval Institute Guide to the Ships and Aircraft of the U.S. Fleet, 15th Edition, Naval Institute Press, 1993.

A2. Sharp, Capt. R., RN, editor, Jane's Fighting Ships 1995-96, 98th Edition, Jane's Information Group Limited, 1995.

Table A3. US Navy ship average annual fuel consumptions, selected classes

CLASS	Number of ships in Class	Average service life left (yrs)	Annual# underway steaming (hours)	Annual fuel consumed underway per ship (barrels)	Data Source of previous 2 columns	Annual fuel for propulsion^ consumed underway per ship (barrels/1000)	Annual fuel for propulsion consumed underway for Class (barrels/1000)
Ticonderoga, CG 47	27	29	2972	85282	VAMOSC, CG47 Class	59.7	1611.8
Spruance/Kidd, DD963&993	35	18	2653	69123	VAMOSC, DD963 Class	48.4	1693.5
Arleigh Burke, DDG 51	50	35	3532	84044	VAMOSC, DDG51 Class	58.8	2941.5
Oliver Hazard Perry, FFG 7	35	24	2809	33960	VAMOSC, FFG7 Class	23.8	832.0
San Antonio, LPD 17	12	35	2400	60000	VAMOSC, LHAs & LHDs*	42.0	504.0
Wasp, LHD 1	6	33	2526	117129	VAMOSC for LHDs	82.0	491.9
Tarawa, LHA 1	5	18	2208	103373	VAMOSC for LHAs	72.4	361.8
Whidbey/Harpers, LSD41&49	12	30	2638	34369	VAMOSC, LSD41 Class	24.1	288.7
Henry J Kaiser, TAO 187	16	31	2400	61900	VAMOSC, A0177*	43.3	693.3
Cimarron (Jumbo), AO 177	5	22	2371	45664	VAMOSC, A0177 Class	32.0	159.8
Supply, AOE 6	4	35	2430	87172	VAMOSC, AOE1*	61.0	244.1

#Annual data presented reflects averaged data from FY92 through FY94
*Estimate from VAMOSC data extrapolated to account for displacement and installed horsepower variations
^Annual fuel consumed for propulsion estimated as 70 percent total fuel consumed underway

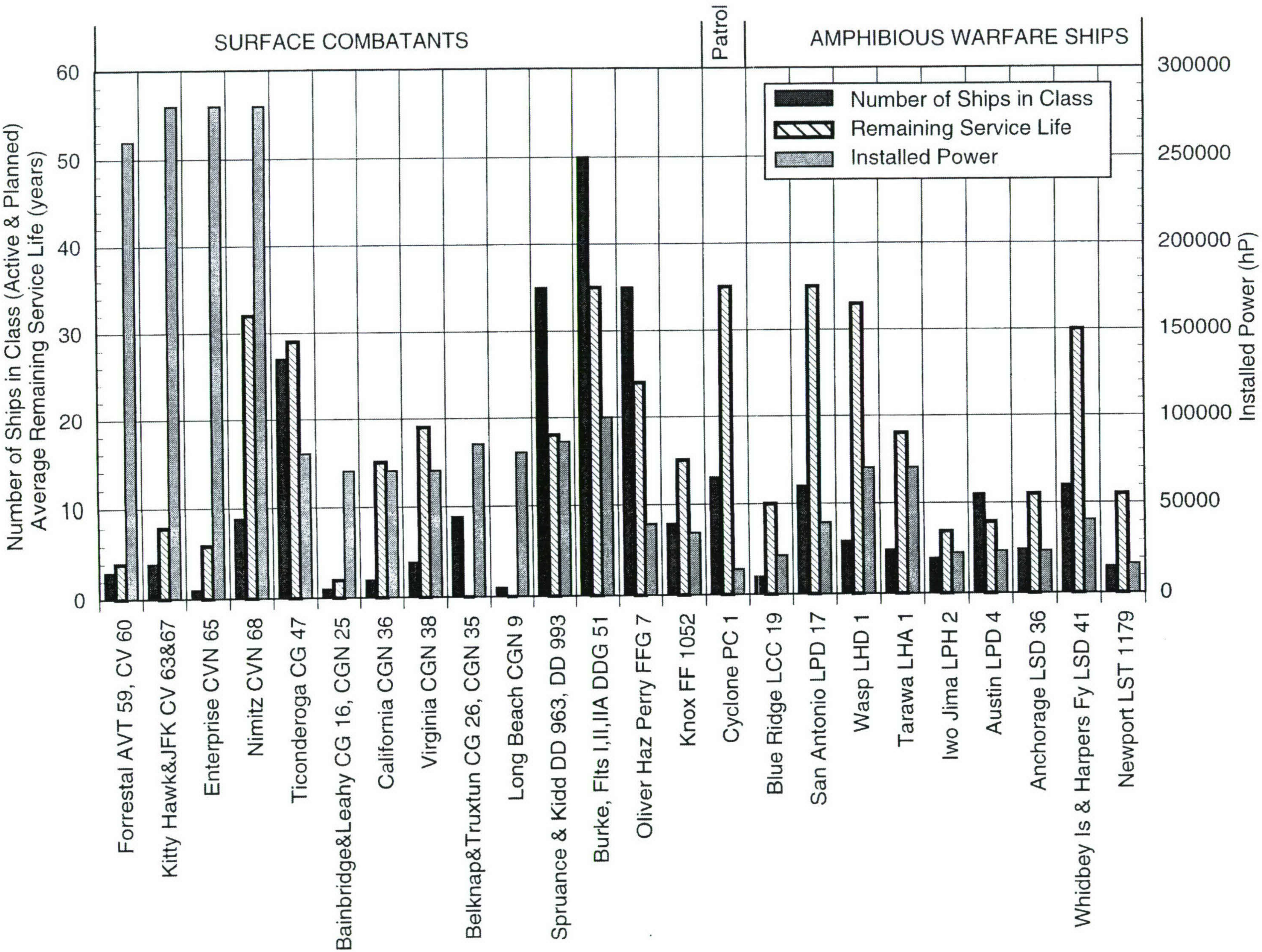


Fig A1a. Number of ships in class, remaining service life, and installed power

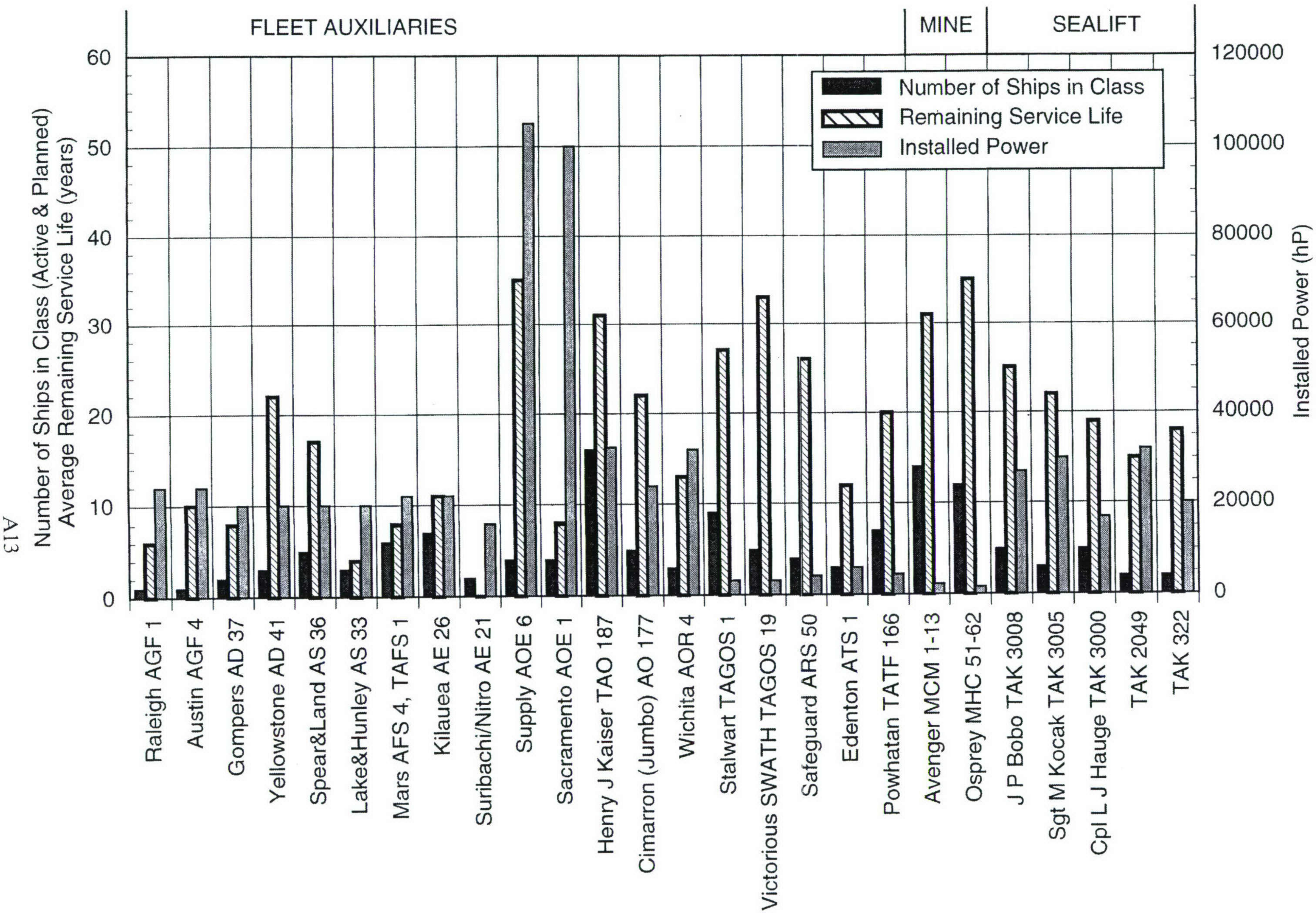


Fig A1b. Number of ships in class, remaining service life, and installed power (continued)

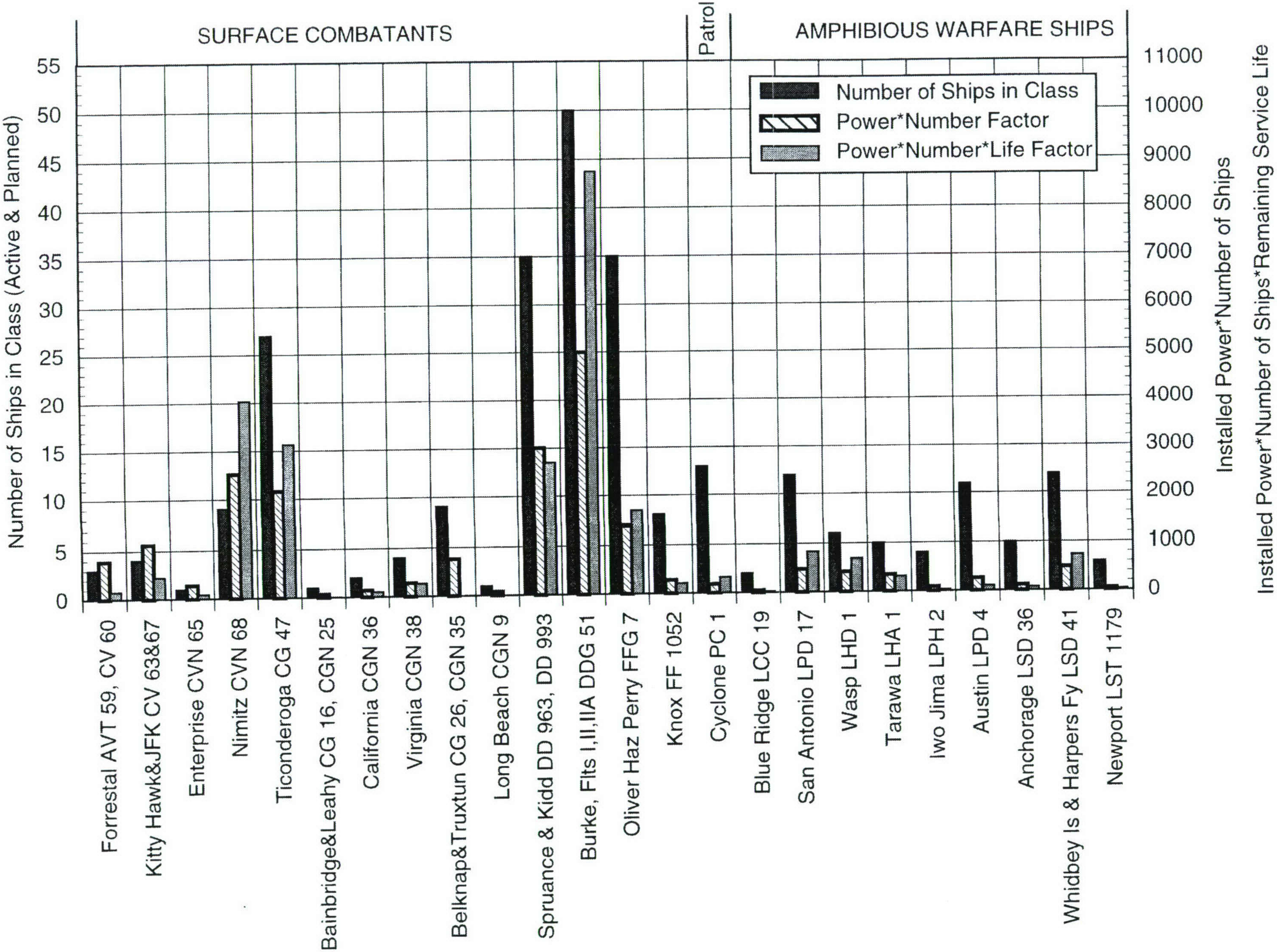


Fig A2a. Number of ships in Class, Power factors and Power-Life factors

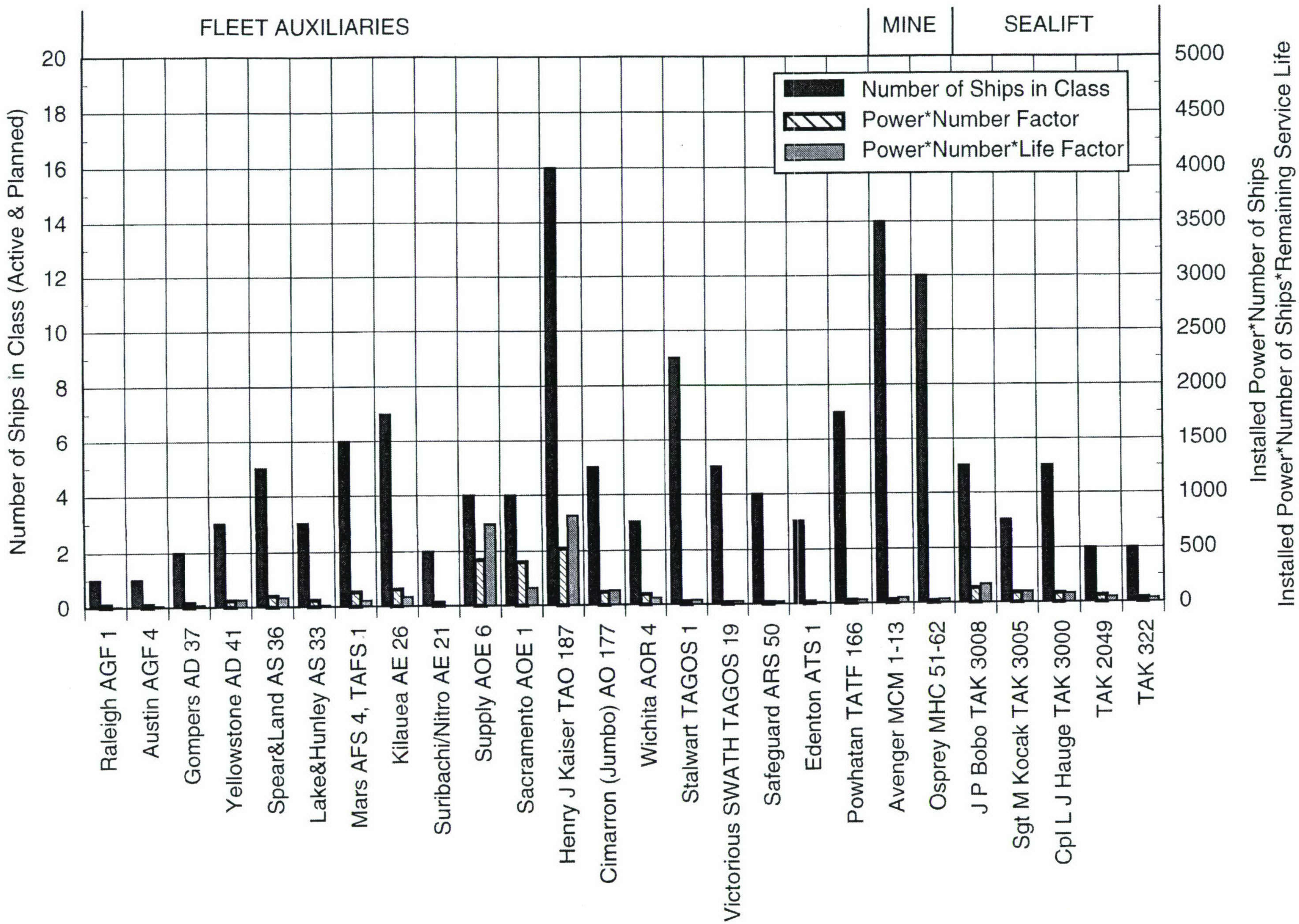
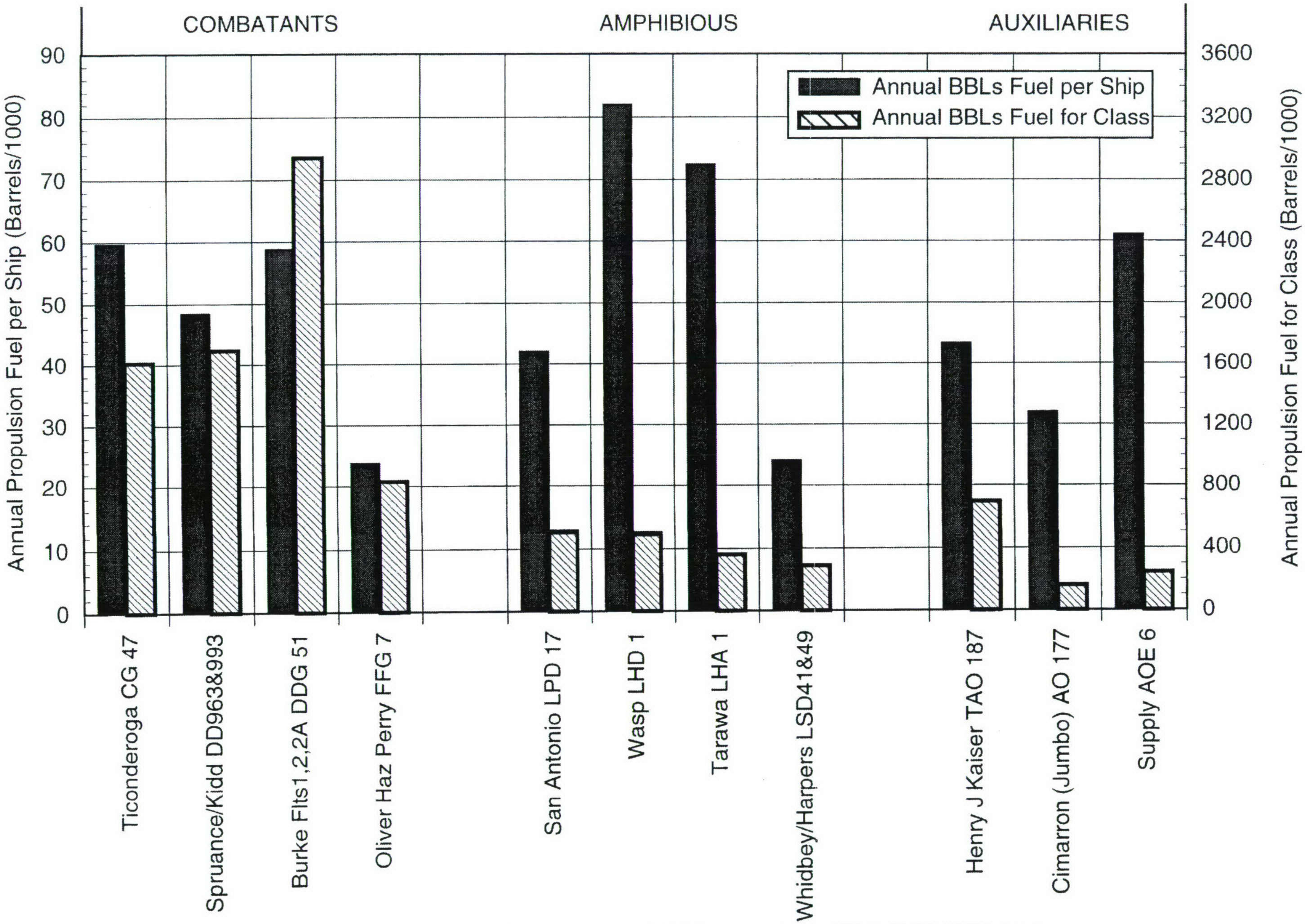


Fig A2b. Number of ships in Class, Power factors and Power-Life factors (continued)



(Anual Fuel Usage Source: Navy VAMOSC averaged from FY92, FY93, FY94 data)

Fig A3. Individual ship and Class averaged annual barrels of fuel used for propulsion

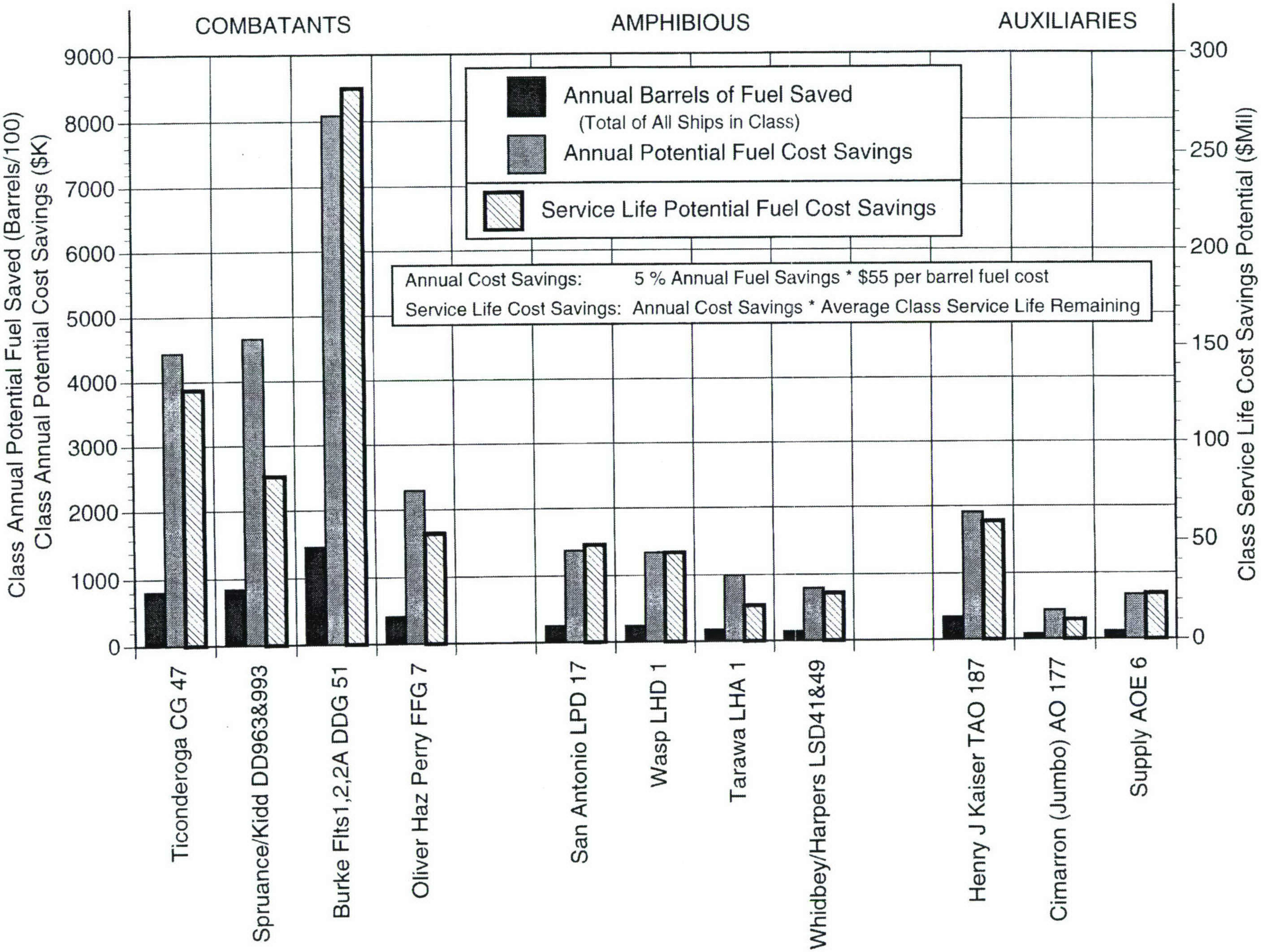


Fig A4. Annual and life-cycle potential fuel cost savings for a 5% energy savings device

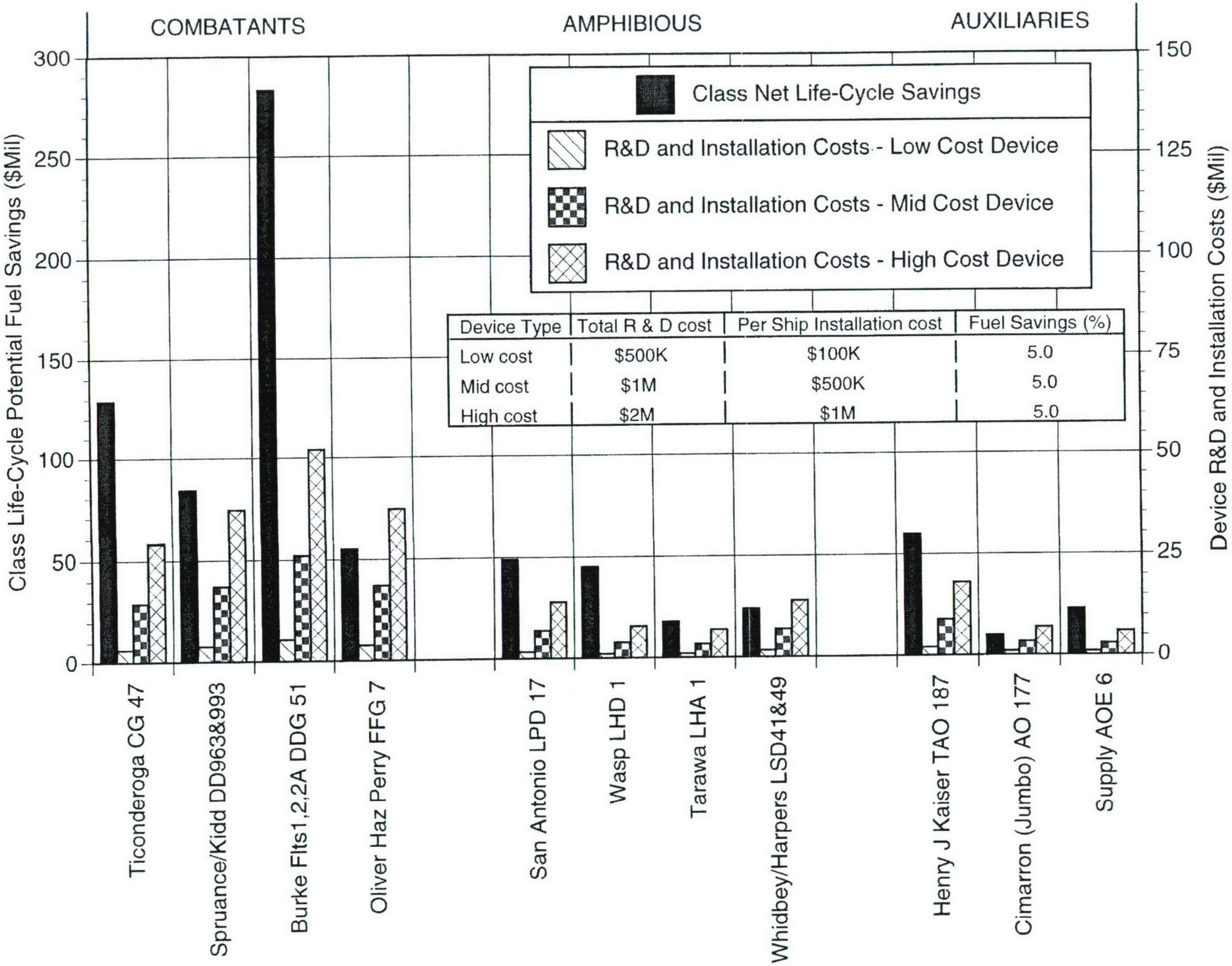


Fig A5. Potential fuel cost savings, estimated R&D and installation costs, of various 5% energy savings devices

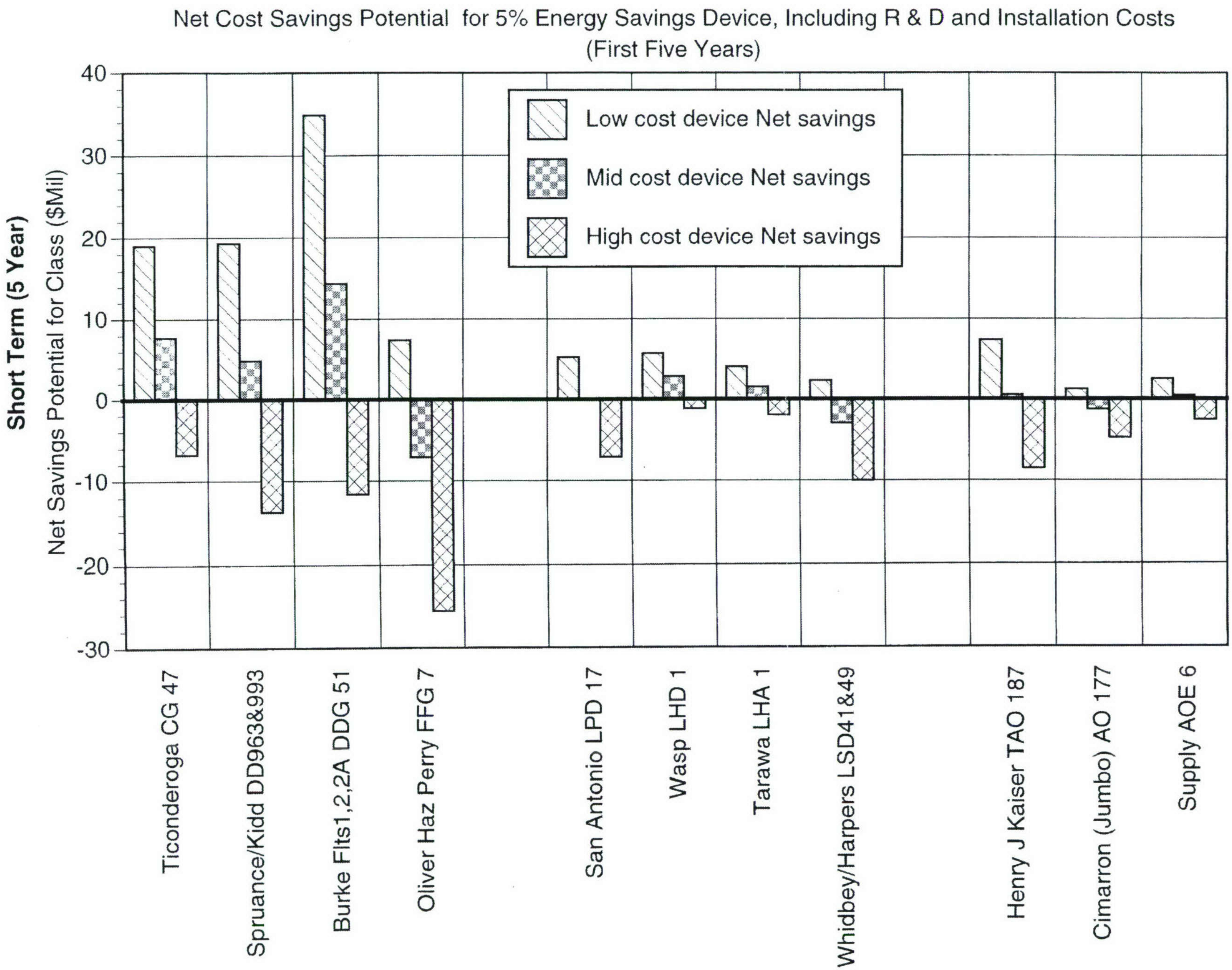


Fig A6. Five-year net cost savings potential for hypothetical 5% energy savings devices

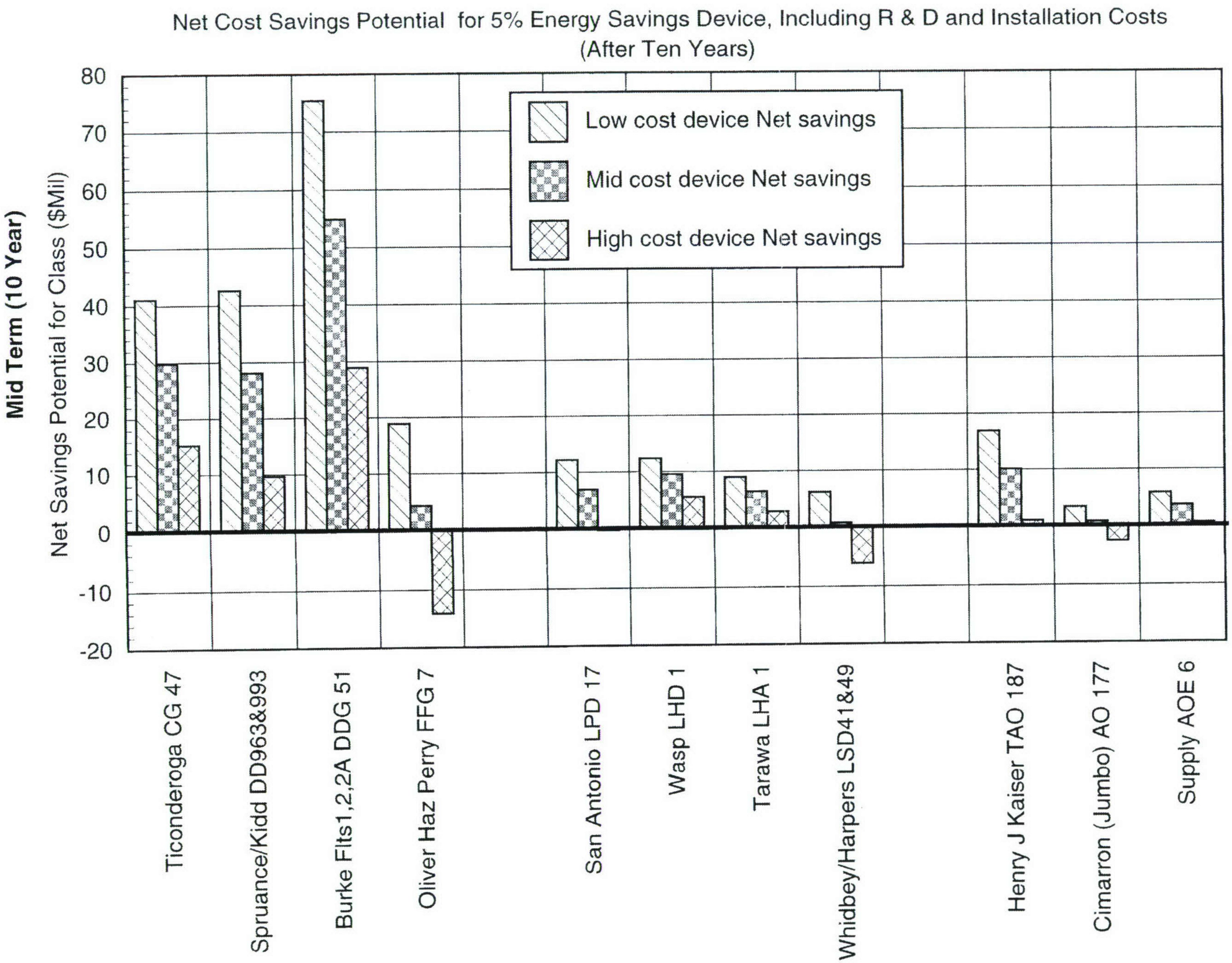


Fig A7. Ten-year net cost savings potential for hypothetical 5% energy savings devices

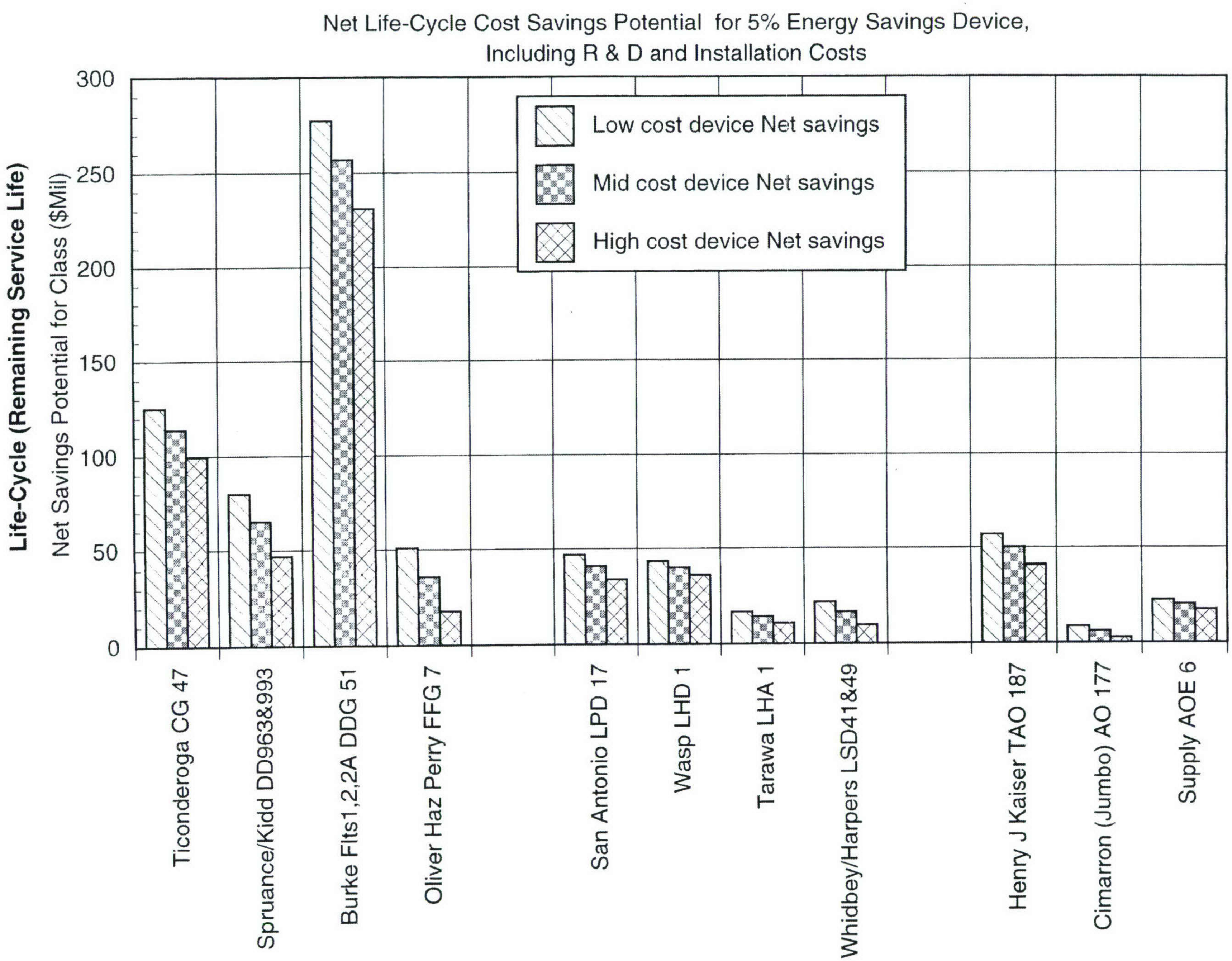


Fig A8. Life-cycle net cost savings potential for hypothetical 5% energy savings devices

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APPENDIX B:

ENERGY SAVINGS DEVICES AND CONCEPTS

It is assumed that competent ship design and naval architecture have already been applied to the US Navy hullforms contained in this study. That is, basic optimization of the hullform has been considered in the areas of: hull main dimensions; hull ratios such as length/beam, beam/draft, etc.; and basic hydrodynamic principles have been applied to the hull lines. Also assumed is that propeller design and sizing, and main propulsion plant considerations, have all been taken into account. The primary means, by which to save shipboard energy, is this correct sizing and design of the vessel and its propulsor. Jumboizing (adding a ship parallel middle body), or the removal of a parallel middle body, are not considered as energy enhancement options in this report.

The data contained in Appendix B is a broad survey of energy enhancing concepts and devices, which have a potential for improving ship energy efficiency. A tremendous number of alternatives, in terms of ship types and shapes, hull innovations, shipboard devices, designs, and concepts, are available to the ship designer, and are reviewed later in this appendix. The individual identified devices and concepts were grouped into three main categories: (A) HULL, (B) APPENDAGE(s), and (C) PROPULSOR(s). The devices and concepts were grouped so that similar devices, or devices that performed under similar principles of operation, were organized together. This resulted in approximately thirty-five (35) organizational groups of devices and concepts. The categorization and organization, of the identified potential energy savings devices and concepts, are presented in the following Table B1.

Henceforth, in this text, any design, device, concept, or organizational grouping of similar devices and concepts, shall all be referred to under the common designation of "device".

After identification, the second step in the process was to provide descriptions of the potential energy savings devices. These descriptions were to include any/all of the following: depiction of the geometry or general appearance of the device, mechanisms or principles of operation, practical considerations, full scale applications or model scale experiences, and if possible, delivered power (or fuel) reduction potential. Also, along with descriptions, photographs, drawings, and/or sketches, are presented of the devices, when available. Within each description is mention of a prominent reference or references for that device, again if available. A list of these references is presented on the last page of Appendix B. The descriptions are presented for each of the thirty-five (35) device groups specified above. Each description is applicable to all of the devices in a common group, except for a few instances, where noted. These thirty-five descriptions of the potential energy savings devices are what compose the main body of Appendix B. A concise listing of these possible energy savings devices, identified as applicable to US Navy ships, is presented in Table B2. Table B2 contains summary information on the energy devices as to their possibility for retrofit, suitability for combatants, amphibious ships, and/or auxiliaries, and very brief comments.

Table B1. Categorization of the identified potential energy savings devices

Category (A) HULL		Category (B) APPENDAGE(s)		Category (C) PROPULSOR(s)	
Group	Device Identification	Group	Device Identification	Group	Device Identification
1	Bulbous Bow, Traditional	12	Duct Upstream of Propeller	26	New Propeller Design
2	Bow Bulb: Small, Near-Surface		Hitachi Zosen (HZ) Nozzle	27	Low RPM/Large Dia Propellers
3	Bulbous Stern		Mitsui Integrated Duct (MIDP)	28	Overlapping Propellers
	Bulbous Skeg		Wake Equalizing Duct (ZAD)	29	Energy Efficient Tip Propellers
4	Stern End Bulbs	13	Flow Fins on Hull		Kappel Propellers
5	Stern Tunnel(s)		Fins to Reduce Bilge Vortex		Concentrated Tip Loaded (CLT)
6	Asymmetric Gondola		Grothues (HDF) Spoiler	30	Contra-Rotating Propellers
	Off Center Propeller		Profiled Strut Arms	31	Tandem Propellers
7	Asymmetric Stern		Wake Adapting Fins	32	Propeller Fairwater Designs
	Cochlea Stern	14	Stator Upstream of Propeller	33	Fins (Blades) on Propeller Hub
8	Extended Skeg		Double Guide Fins		Propeller Boss Cap Fin
9	Twin Skegs		Inflow Control Vanes		Post Swirl Cap
10	Propulsion Pods		Stream Control Installation	34	Vane (Grim) Wheel
11	Numeric Optimized Forebody	15	Ducted Inflow Control Vanes	35	Propeller Pitch Scheduling
			Reaction(tive) Fins		
		16	Ducted Propeller(s)		
		17	Stator Behind Propeller		
		18	Bearing in Rudder Post		
		19	Main Strut Barrel Designs		
		20	Alternative Rudder Designs		
			Contra-Guide Rudder		
			Rudder with Costa Bulb		
			Split Rudder		
		21	Thrusting Fins on Rudder		
			Additional Thrusting (AT) Fin		
			Profiling Fins on Rudder		
			Rudder-Bulb-Fin		
		22	Steering Nozzle		
		23	Semi Tunnel Nozzle		
			Semi-Duct		
		24	Sterntube		
		25	Stern Flap		
			Stern Wedge		

The device descriptions presented were extracted from a wide variety of different types of media sources. The following are the three main types of media sources taken into consideration:

- (1) US Navy research and development programs. The data was extracted from both open publication reports, journals, and technical presentations, and from limited distribution unclassified reports.

- (2) Foreign and domestic R&D programs. The data was extracted from referenceable open publication reports, journals, and similar technical documents.

- (3) Foreign and domestic commercial shipbuilding industries. The data was extracted most generally from advertising material of a technical nature for a particular device, from company brochures and promotional literature, or from magazines and journals. Some of the information was extracted from referenceable technical documents.

A chart of compatibility between all identified energy savings devices was prepared, and is presented as Table B3. Again, the individual energy savings devices are represented in their respective groupings. For the purpose of condensation of this table, the thirty-five groups are identified by only the title of the first individual device in that group. The stated compatibility is equivalent for all devices in any particular group. The practicality of equipping a single hullform with all identified compatible devices is not within the scope of Table B3. It is simply a presentation of the material limitations on compatibility between devices. Device compatibility, in Table B3, is labeled in four different classifications. Device compatibility classification is as follows:

- (C) COMPATIBLE: These two devices perform under different principles of operation, and/or occupy different (non-overlapping) positions on the ship hullform.
- (N) NOT COMPATIBLE: These two devices either perform under equivalent principles of operation, and/or occupy similar (overlapping) positions on the ship hullform.
- (PC) PARTIALLY COMPATIBLE: These two devices could be used together on a hullform, however, either/or the following applies:
  a) The use of both devices may inhibit the full performance potential of either.
  b) Both devices perform under related principles of operation.
  c) For practicality considerations, both devices would not likely be utilized together.
- (D) DIFFERENT HULL DESIGNS: These two devices are designed to operate on dissimilar hulls or hullform types.

The energy device groups were then subjected through a selected process for potential retrofit to US Navy surface ships. The criteria for this selection process was:

- (1) The device had to be practical as a retrofit. Those devices that are exclusively new designs, or for some identified reason classified as non-retrofittable, were eliminated from further considerations.
- (2) The device had to be reliable and durable enough for use on US Navy ships.
- (3) The device had to have a history of demonstrated energy enhancement potential (model or full scale) on some ship similar to a possible US Navy present or future application.
- (4) The energy savings devices had to be applicable to at least one of the US Navy ship classes identified in the first part of the study, or had to be applicable to foreseeable future Navy hullforms. Devices suitable to only high block coefficient, relatively slow speed, commercial or merchant type hulls, with single-screw heavily loaded propellers, were not selected.

A summary is presented in Table B4 of the selection or elimination of the energy devices, and criteria for the selection or elimination. Fourteen (14) energy savings devices were selected as applicable for retrofit to a present US Navy hullform design. These devices satisfied all of the aforementioned criteria. The selected devices included three from Category (A) Hull, five from Category (B) Appendage(s), and six from Category (C) Propulsor(s). A simple listing of the candidate retrofit energy savings devices are presented in the following Table B5:

Table B5. Selected candidate retrofit energy savings devices

Selected Candidate Retrofit Energy Savings Devices		
Category (A) Hull	Category (B) Appendage(s)	Category (C) Propulsor(s)
Bulbous Bow, Traditional	Stator Upstream of Propeller	New Propeller Design
Bow Bulb, Small, Near-Surface	Main Strut Barrel Designs	Low RPM / Large Diameter Propeller
Stern End Bulb	Alternative Rudder Designs	Energy Efficient Tip Propeller
	Thrusting Fins on Rudder(s)	Propeller Fairwater Designs
	Stern Flap, Stern Wedge	Fins (Blades) on Propeller Hub
		Propeller Pitch Scheduling

Lastly, a chart listing the fourteen (14) selected candidate energy savings devices, and recommendations for retrofit on the eleven (11) identified US Navy Classes, is presented in Table B6. This table represents, in basis, a summary of the entire identification, classification, and selection process. Table B6 also indicates the following information on each selected candidate energy savings device:

- (R) Device is Recommended for retrofit on this ship class
- (C) Device should be Considered for retrofit on this ship class
- (S) Device is Suitable for this ship class
- (M) Model tests have previously been conducted with this type of device on this ship class
- (D) Design of ship hull presently includes this type of device

The descriptions of the potential energy savings devices (main body of Appendix B) are presented after the final table (Table B6). Again, these descriptions are separated into three categories: (A) Hull, (B) Appendage(s), and (C) Propulsor(s), and further sub-divided into thirty-five organizational device groupings.

Table B2. List of possible energy savings devices

No.	CATEGORY	(R)etrofit (N)ew Design	(C)ombatants (AMP)hibious (AUX)illiaries	Brief Comments
No.	**(A) HULL**			
1	Bulbous Bow, Traditional	R, N	C, AMP, AUX	reduced hull resistance
2	Bow Bulb: Small, Near-Surface	R, N	C, AMP, AUX	reduced hull resistance, designed to be used on bows with sonar domes
3	Bulbous Stern Bulbous Skeg	N	AUX	for single-screw, high block hulls, favorable prop-hull interaction coeffs
4	Stern End Bulbs	R	AUX	reduced hull resistance
5	Stern Tunnel(s)	N	C, AMP, AUX	used in combination with large dia propeller
6	Asymmetric Gondola Off Center Propeller	N	AUX	generate pre-swirl into propeller
7	Asymmetric Stern Cochlea Stern	N	AUX	generate pre-swirl into propeller technology in commercial applications
8	Extended Skeg	N	C, AMP, AUX	elongation of underwater hull
9	Twin Skegs	N	AUX	favorable interaction coefficients
10	Propulsion Pods	N	C, AMP, AUX	for electric drive, long-term R&D
11	Numerically Optimized Forebody	N	C, AMP, AUX	reduced hull resistance
No.	**(B) APPENDAGE(s)**			
12	Duct Upstream of Propeller Hitachi Zosen (HZ) Nozzle Mitsui Integrated Duct (MIDP) Wake Equalizing Duct (ZAD)	R, N	AUX	all: reduce vorticies, homogenize flow, generally for single-screw, high block coefficient hulls technology in commercial applications
13	Flow Fins on Hull Fins to Reduce Bilge Vortex Grothues (HDF) Spoiler Profiled Strut Arms Wake Adapting Fins	R	AUX	all: reduce vorticies, homogenize flow, generally for high block coefficient hulls technology in commercial applications
14	Stator Upstream of Propeller Double Guide Fins Inflow Control Vanes Stream Control Installation	R, N	C, AMP, AUX	all: homogenize flow, and generate pre-swirl into propeller, and attempt to augment thrust
15	Ducted Inflow Control Vanes Reaction(tive) Fins	R, N	C, AMP, AUX	both: generate pre-swirl, homogenize flow into propeller, utilize flow ducts
16	Ducted Propeller(s)	R, N	C, AMP, AUX	flow control for heavily loaded propellers
17	Stator Behind Propeller	R, N	C, AMP, AUX	regain lost rotational energy
18	Bearing in Rudder Post	N	C, AMP, AUX	eliminate shaft struts
19	Main Strut Barrel Designs	R, N	C, AMP, AUX	reduced appendage resistance
20	Alternative Rudder Designs Contra-Guide Rudder Costa Bulb Rudder Split Rudder	R, N	C, AMP, AUX	increase swirl recovery
21	Thrusting Fins on Rudder(s) Additional Thrusting (AT) Fin Profiling Fins on Rudder Rudder-Bulb-Fin	R	C, AMP, AUX	all: regain lost rotational energy in propeller race (increase swirl recovery) technology in commercial applications
22	Steering Nozzle	N	C, AMP, AUX	for heavily loaded propellers
23	Semi Tunnel Nozzle Semi-Duct	N	AUX	combination tunnel and semi-duct combination fins and duct
24	Sterntube	N	C, AMP, AUX	eliminate shaft struts
25	Stern Flap Stern Wedge	R	C, AMP, AUX	both: easily backfit, reduce hull resistance, increase efficiency proven technology in US Navy applications

Table B2. List of possible energy savings devices (continued)

No.	CATEGORY	(R)etrofit (N)ew Design	(C)ombatants (AMP)hibious (AUX)illiaries	Brief Comments
	(C) PROPULSOR(s)			
26	New Propeller Design	R, N	C, AMP, AUX	improved efficiency propeller
27	Low RPM / Large Dia Propellers	R, N	C, AMP, AUX	improved efficiency, used with tunnel stern
28	Overlapping Propellers	N	C, AMP, AUX	reduce loading, increase efficiency
29	Energy Efficient Tip Propellers Kappel Propellers Concentrated Tip Loaded (CLT)	R, N	C, AMP, AUX	all: increased loading at blade tips for increased efficiency
30	Contra-Rotating Propellers	N	C, AMP, AUX	improved effic, high cost and long-term R&D
31	Tandem Propellers	N	C, AMP, AUX	improved efficiency, reduced acoustics
32	Propeller Fairwater Designs	R	C, AMP, AUX	reduce hub drag and losses
33	Fins (Blades) on Propeller Hub Propeller Boss Cap Fin Post Swirl Cap	R	C, AMP, AUX	all: reduce propeller hub vortex losses technology in commercial applications
34	Vane (Grim) Wheel	R, N	AUX	regain rotational and axial losses technology in commercial applications
35	Propeller Pitch Scheduling	R	C, AMP, AUX	increase engine efficiency at specified speeds

No.	Device	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
No.	**(A) HULL**																																			
1	Bulbous Bow, Traditional	1	N	C	C	C	C	C	C	C	C	PC	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
2	Bow Bulb: Small, Near-Surface		2	C	C	C	C	C	C	C	C	PC	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
3	Bulbous Stern			3	C	C	D	D	C	D	D	C	C	C	C	C	C	C	D	D	C	C	C	C	D	C	C	C	C	C	C	C	C	C	C	C
4	Stern End Bulbs				4	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	N	C	C	C	C	C	C	C	C	C	C
5	Stern Tunnel(s)					5	D	PC	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
6	Asymmetric Gondola						6	D	D	PC	D	C	C	C	C	C	C	C	D	D	C	C	C	D	D	C	C	C	C	C	C	C	C	C	C	C
7	Asymmetric Stern							7	PC	D	D	C	C	C	C	C	C	C	D	D	C	C	C	C	D	C	C	C	C	C	C	C	C	C	C	C
8	Extended Skeg								8	PC	D	C	C	C	C	C	C	C	D	D	C	C	C	C	D	C	C	C	C	C	C	C	C	C	C	C
9	Twin Skegs									9	D	C	C	C	C	C	C	C	D	D	C	C	C	C	D	C	C	C	C	C	C	C	C	C	C	C
10	Propulsion Pods										10	C	N	N	C	C	C	C	D	D	C	C	PC	D	D	C	C	C	C	C	C	C	C	C	PC	C
11	Numerically Optimized Forebody											11	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
No.	**(B) APPENDAGE(s)**																																			
12	Duct Upstream of Propeller												12	PC	N	N	N	C	PC	N	C	C	C	N	N	C	C	C	C	C	C	C	C	C	C	C
13	Flow Fins on Hull													13	N	N	C	C	D	D	C	C	C	C	D	C	C	C	C	C	C	C	C	C	C	C
14	Stator Upstream of Propeller														14	N	C	C	C	C	C	C	C	PC	C	C	C	C	PC	C	N	N	C	C	C	C
15	Ducted Inflow Control Vanes															15	N	PC	C	C	C	C	N	N	C	C	C	C	N	C	C	C	C	C	C	C
16	Ducted Propeller(s)																16	C	C	C	C	C	N	N	C	C	C	C	N	C	C	C	C	C	PC	C
17	Stator Behind Propeller																	17	C	C	C	C	N	C	C	C	C	PC	N	C	N	C	C	PC	N	C
18	Bearing in Rudder Post																		18	C	C	C	N	D	C	C	C	C	C	C	C	C	N	N	PC	C
19	Main Strut Barrel Designs																			19	C	C	C	D	PC	C	C	C	C	C	C	C	C	C	C	C
20	Alternative Rudder Designs																				20	C	N	C	C	C	C	C	C	C	PC	C	C	C	C	C
21	Thrusting Fins on Rudder(s)																					21	N	C	C	C	C	C	C	C	PC	C	C	C	C	C
22	Steering Nozzle																						22	N	C	C	C	C	N	C	C	C	C	C	PC	C
23	Semi Tunnel Nozzle																							23	D	C	C	C	C	C	C	C	C	C	C	C
24	Sterntube																								24	C	C	C	C	C	C	C	C	C	C	C
25	Stern Flap																									25	C	C	C	C	C	C	C	C	C	C
No.	**(C) PROPULSOR(s)**																																			
26	New Propeller Design																										26	C	C	C	C	C	C	C	C	C
27	Low RPM / Large Dia Propellers																											27	C	C	C	C	C	C	PC	C
28	Overlapping Propellers																												28	C	N	N	C	C	N	C
29	Energy Efficient Tip Propellers																													29	PC	C	C	C	PC	C
30	Contra-Rotating Propellers																														30	N	C	PC	N	N
31	Tandem Propellers																															31	C	C	PC	N
32	Propeller Fairwater Designs																																32	C	N	C
33	Fins (Blades) on Propeller Hub																																	33	N	C
34	Vane (Grim) Wheel																																		34	PC
35	Propeller Pitch Scheduling																																			35

C COMPATIBLE
PC PARTIALLY COMPATIBLE
N NOT COMPATIBLE
D DEVICES SUITABLE FOR DIFFERENT HULL DESIGNS

Table B3. Potential compatibility between energy savings devices

Table B4. Summary of selection and elimination of candidate energy savings devices

No.	CATEGORY	Selection for Further Study	Criteria for Selection or Elimination
	(A) HULL		
1	Bulbous Bow, Traditional	**Selected**	high energy savings
2	Bow Bulb: Small, Near-Surface	**Selected**	high energy savings, low cost
3	Bulbous Stern Bulbous Skeg	Eliminated	exclusively new design
4	Stern End Bulbs	**Selected**	high savings, low cost
5	Stern Tunnel(s)	Eliminated	exclusively new design
6	Asymmetric Gondola Off Center Propeller	Eliminated	exclusively new design
7	Asymmetric Stern Cochlea Stern	Eliminated	exclusively new design
8	Extended Skeg	Eliminated	exclusively new design
9	Twin Skegs	Eliminated	exclusively new design
10	Propulsion Pods	Eliminated	exclusively new design
11	Numerically Optimized Forebody	Eliminated	exclusively new design

No.	CATEGORY	Selection for Further Study	Criteria for Selection or Elimination
	(C) PROPULSOR(s)		
26	New Propeller Design	**Selected**	mod-high energy savings
27	Low RPM / Large Dia Propellers	**Selected**	mod-high energy savings
28	Overlapping Propellers	Eliminated	exclusively new design
29	Energy Efficient Tip Propellers Kappel Propellers Concentrated Tip Loaded (CLT)	**Selected**	mod-high energy savings commercially available
30	Contra-Rotating Propellers	Eliminated	exclusively new design
31	Tandem Propellers	Eliminated	exclusively new design
32	Propeller Fairwater Designs	**Selected**	very low cost
33	Fins (Blades) on Propeller Hub Propeller Boss Cap Fin Post Swirl Cap	**Selected**	mod savings, low cost commercially available
34	Vane (Grim) Wheel	Eliminated	reliability in question
35	Propeller Pitch Scheduling	**Selected**	possible savings, no cost

No.	CATEGORY	Selection for Further Study	Criteria for Selection or Elimination
	(B) APPENDAGE(s)		
12	Duct Upstream of Propeller Hitachi Zosen (HZ) Nozzle Mitsui Integrated Duct (MIDP) Wake Equalizing Duct (ZAD)	Eliminated	best suited for single screw, high block hulls, heavy loaded propellers
13	Flow Fins on Hull Fins to Reduce Bilge Vortex Grothues (HDF) Spoiler Profiled Strut Arms Wake Adapting Fins	Eliminated	best suited for single screw, high block hulls, heavy loaded propellers
14	Stator Upstream of Propeller Double Guide Fins Inflow Control Vanes Stream Control Installation	**Selected**	mod-high energy savings US Navy experience with inflow control vanes
15	Ducted Inflow Control Vanes Reaction(tive) Fins	Eliminated	significant R&D necessary
16	Ducted Propeller(s)	Eliminated	poor energy reducer
17	Stator Behind Propeller	Eliminated	non-standard prop neces.
18	Bearing in Rudder Post	Eliminated	exclusively new design
19	Main Strut Barrel Designs	**Selected**	low-mod energy savings
20	Alternative Rudder Designs Contra-Guide Rudder Costa Bulb Rudder Split Rudder	**Selected**	low-mod energy savings commercially available
21	Thrusting Fins on Rudder(s) Additional Thrusting (AT) Fin Profiling Fins on Rudder Rudder-Bulb-Fin	**Selected**	moderate energy savings low cost commercially available
22	Steering Nozzle	Eliminated	exclusively new design
23	Semi Tunnel Nozzle Semi-Duct	Eliminated	exclusively new design
24	Sterntube	Eliminated	exclusively new design
25	Stern Flap Stern Wedge	**Selected**	high energy savings, low cost, proven US Navy technology

Table B6. Summary of energy savings devices selection, suitability, recommendations for retrofit, and model test history, for identified US Navy Classes

	COMBATANTS				AMPHIBIOUS				AUXILIARIES		
	Ticonderoga CG-47	Spru/Kidd DD963/993	Burke DDG-51	Perry FFG-7	LPD-17	Wasp LHD-1	Tarawa LHA-1	Whid/Harp LSD41&49	Kaiser TAO187	Cimarron AO177	Supply AOE6
No. **(A) HULL**											
1 Bulbous Bow, Traditional				C,S,M	S,M,D	S,M,D	**R**,S,M	S,M,D	**R**,S,M	S,M,D	S,M,D
2 Bow Bulb: Small, Near-Surface	**R**,S,M	**R**,S,M	**R**,S,M	C,S			C,S		C,S		
4 Stern End Bulb	S	S	S	S					C,S	C,S	C,S,M
No. **(B) APPENDAGE(s)**											
14 Stator Upstream of Propeller	S	S	S	S,M	S	**R**,S	**R**,S	S	**R**,S	S	S
19 Main Strut Barrel Designs	S	S	S	S	S	S	S	S	S		S
20 Alternative Rudder Designs	S	S	S	S	C,S	C,S	C,S	C,S	C,S	**R**,S	C,S
21 Thrusting Fins on Rudder(s)	S	S	S	S	C,S	C,S	C,S	C,S	C,S	**R**,S	C,S
25 Stern Flap, Stern Wedge	**R**,S,M	**R**,S,M	**R**,S,M,D	**R**,S,M,D	**R**,S,M,D	**R**,S	**R**,S	**R**,S	**R**,S	**R**,S	**R**,S
No. **(C) PROPULSORS(s)**											
26 New Propeller Design	S	S	S,M,D	S	S,M,D	S	S	**R**,S	S	S	**R**,S
27 Low RPM / Large Dia Propeller	S,M	S,M	S	S	S	S	S	S	S	S	S
29 Energy Efficient Tip Propeller					S	S	S	**R**,S	S	S	C,S
32 Propeller Fairwater Designs	C,S	C,S,M	C,S	C,S	C,S	C,S	C,S	C,S	**R**,S	C,S	C,S
33 Fins (Blades) on Propeller Hub	S	S	S	S	**R**,S	**R**,S	**R**,S	**R**,S	C,S	C,S	C,S
35 Propeller Pitch Scheduling	**R**,S	**R**,S,M,D	**R**,S	**R**,S	**R**,S*			**R**,S	**R**,S		

R Recommended for Retrofit on this ship
C Consideration should be given to Retrofit on this ship
S Device is potentially Suitable for use on this ship
M Model tests have previously been conducted on this hull design with this type of device
D Design of ship hull presently includes this device

* The Navy has not determined if final configuration will be fixed-pitch or controllable-pitch propellers on LPD-17 Class

CATEGORY (A) HULL

(1) Bulbous Bow, Traditional

Traditional bulbous bows, Figure B1, are a well recognized, and well accepted, means of reducing hull resistance, and therefore reducing powering requirements. The reduction in drag is derived primarily by the lowering of wavemaking resistance through attenuation of the bow wave system of the ship, and possibly to a lesser extent reducing wave breaking, and by the reduction of viscous resistance due to a smoothing of the flow around the forebody. Numerous examples of traditional bulbous bows exist, both full and model scale, and many more variations are well documented. Many references are available from the early part of the century to present, however, Kracht (Ref. B1.a), is a principal design guidance and reference. Bulbous bows offer a very wide application to all ships, with the exception of Naval combatants where hull designs incorporate a sonar dome at the bow. Many successful US Navy ship designs have had bulbous bows, and many of the ship classes identified in energy survey presently include a bulbous bow in their hull design.. Power reductions of as much as 10 percent are possible, however, the magnitude of the power reductions is design speed specific, and speed dependent.

The concept is recommended for further consideration, even though it is more attractive as a new design rather than a backfit. Backfitting of a traditional bulbous bow is possible. However, backfitting would be associated with considerable design, construction, and installation costs, and possible ship integration difficulties. A US Navy study concluded that the anticipated fuel cost savings due to retrofitting bulbous bows will be sufficient to justify bulb fabrication and installation costs on some ship classes (Ref. B1.b). Several of the selected candidate US Navy ship classes presently include bulbous bows: LPD-17, LHD-1, LSD41&49, AO-177, and AOE-6. Additional ships for which this concept is applicable: FFG-7, LHA-1, and TA0-187.

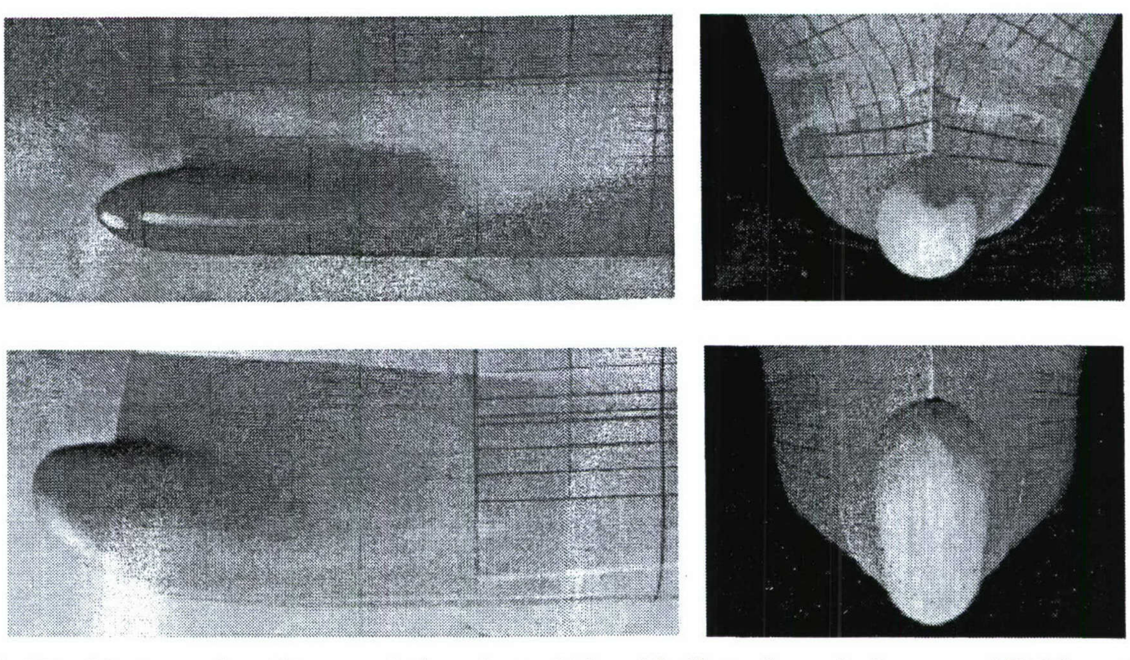


Fig B1. Photographs of two variations in traditional bulbous bow designs, on AE-36 model

(2) Bow Bulb: Small, Near-Surface

The small, near-surface, bow bulb, Figure B2, is a new type of hydrodynamic bulbous bow developed and patented[1] for use with U.S. Navy destroyers and cruisers, (Ref. B2.a). Unlike the traditional bulbous bow (above), the new bulb is integrated into an existing combatant bow which houses a sonar dome. Resistance reductions are achieved similarly to the traditional bulbous bow. Design emphasis is towards a bulb size and shape which would maximize resistance reduction in the speed range most frequented by destroyers, thus increasing the potential for energy reduction. After several iterations on simple-shaped body of revolution bulbs, of varying sizes and volumes, an initial hydrodynamic bulb design was developed for the DDG-51 Class. Model tests show that this initial design bulb significantly reduces ship resistance, and results in an overall decrease in powering of 5.8 percent, and an increase in top speed of 0.5 knots, (Ref. B2.b). Fuel cost savings due to the bow bulb installation has been estimated to be $116K per year per ship, on the DDG-51 Class. Improvements in propeller cavitation characteristics[2], and reductions in signature levels[2] were also exhibited. Model tests with a preliminary bow bulb design, conducted on the CG-47 Class Cruisers, indicate a 2 percent delivered power reduction, (Ref. B2.c). It is expected that with continued design refinement, the delivered power reduction of this device on the CG-47 Class would be improved.

The bow bulb for the DDG-51 was originally conceived and developed as a backfit device. Estimated cost of "first of series" backfit bow bulb is $500K, cost for additional backfits are estimated at $350K per bow bulb, making this concept a low-to-medium cost, high energy savings candidate for further consideration. This technology is applicable to the following US Navy ship classes identified for energy improvement: DDG-51, CG-47, DD-963 and DD-993, FFG-7, LHA-1, and TAO-187 Classes. All other ship classes in survey include a traditional bulbous bow in their hull design.

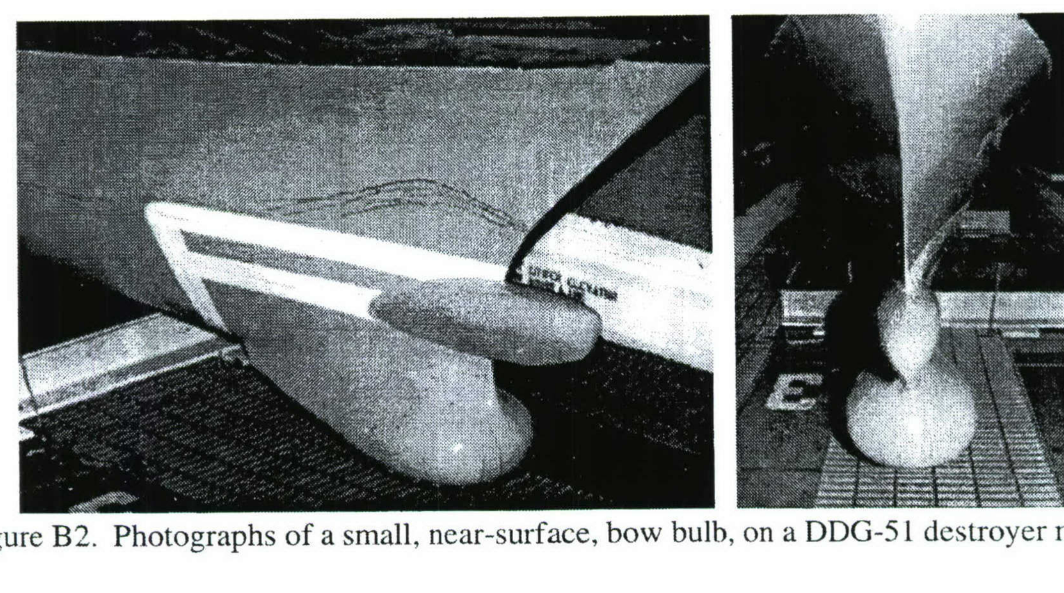


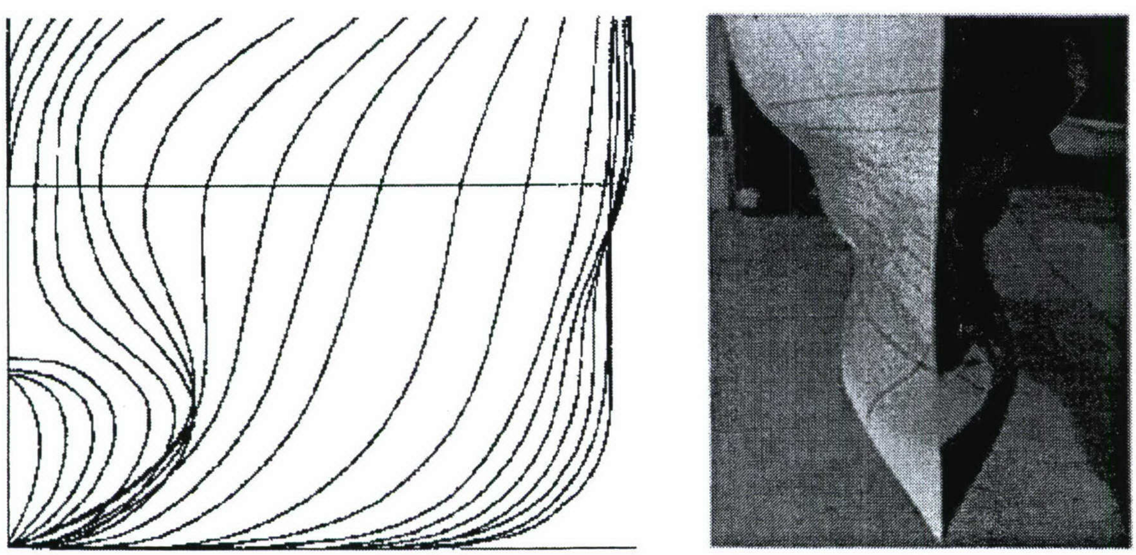
Figure B2. Photographs of a small, near-surface, bow bulb, on a DDG-51 destroyer model

[1] Cusanelli, D.S. and G. Karafiath, "Combined Bulbous Bow and Sonar Dome for a Vessel", US Patent Number 5,280,761, Jan. 1994.

[2] Model and/or full scale test results are of higher classification.

(11) Numerically Optimized Forebody

Numerically optimized forebody, Figure B11, is a concept where existing computational fluid dynamics (CFD) computer codes are utilized in the design process to optimize a forebody shape for minimum wave resistance. Power reductions of as much as 10 -20 percent are possible, however, the magnitude of the power reductions has been extremely specific to the speed for which the forebody was optimized. This concept was recently evaluated during the AE-36 Energy Enhancement Program (Ref. B11.a). The AE-36 Total Resistance Optimized Forebody (TROF) was designed by Science Applications International (SAIC) using an optimizational scheme on a paneled hull with far-field wavemaking resistance predicted using slender body theory (Ref. B11.b). The AE-36 TROF exhibited a remarkable 20 percent reduction in delivered power at the 24 knot design speed, however, it also exhibited an unprecedented increase in power of 42 percent at 14 knots. The results of this application on AE-36 showed a time-averaged powering increase (factored for speed-time-loading profile) of nearly 24 percent, resulting solely from the low speed resistance increases. Also, at the light ballast load draft, a condition for which the bow was not optimized, the AE-36 TROF exhibited a resistance of more than double the baseline bow. Implementation of this technology as an energy reduction concept would require significant R&D work. Non-linear, near-field, free surface phenomena need to be included in the forebody optimization. The optimization should be for a complete ship speed range and displacement operational scenario. Free surface wave properties, especially those properties that affect wave breaking, should also be included. The numerically optimized forebody concept is not considered further in the present energy study, because it is exclusively a new construction item.



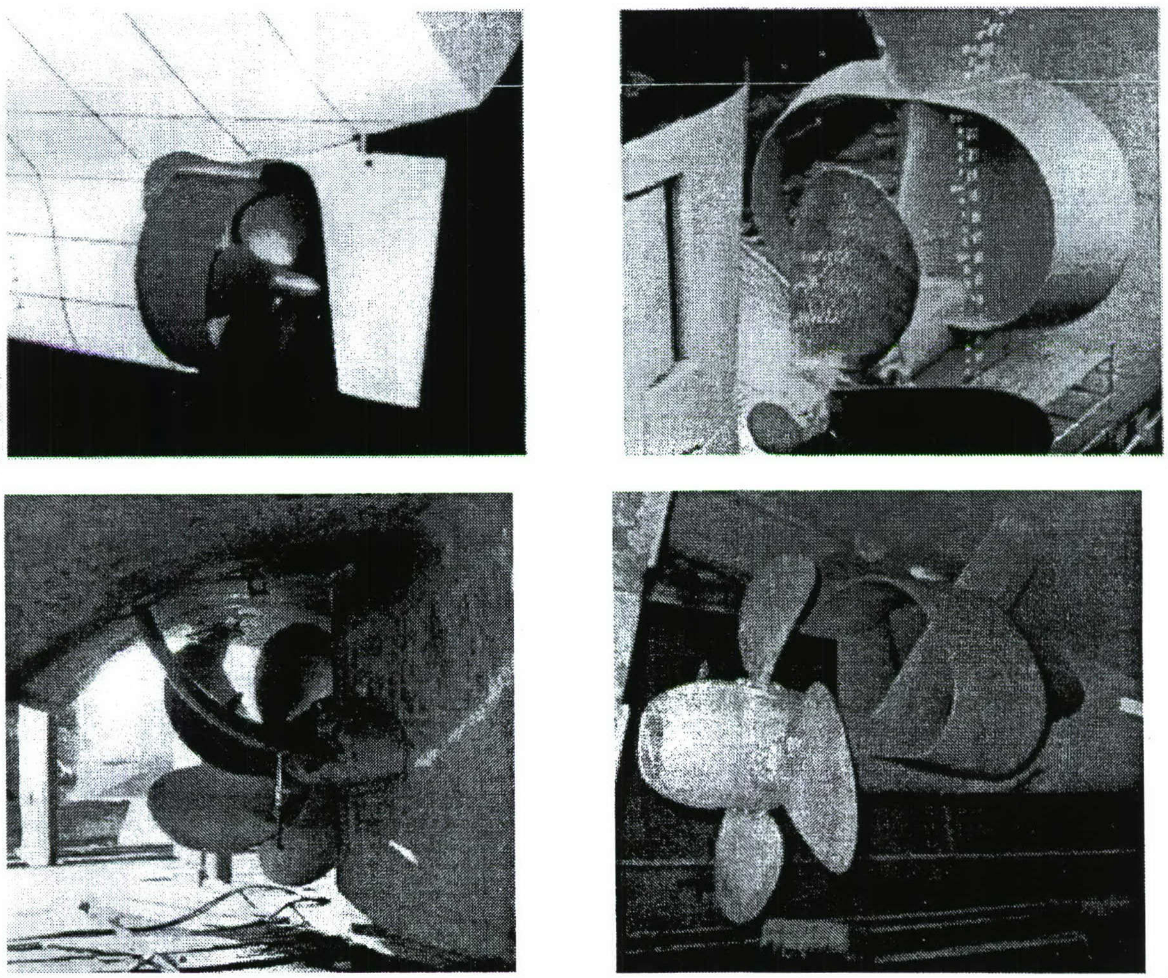
(a) (b)

Fig B11. AE-36 Total Resistance (numerically) Optimized Forebody. (a) Sketch of forebody plan, and (b) close-up photograph of model showing design details in bow region

CATEGORY (B) APPENDAGE(s)

(12) Duct Upstream of Propeller, Mitsui Integrated Ducted Propeller (MIDP), Hitachi Zosen (HZ) Nozzle, Wake Equalizing Duct (ZAD)

These concepts are all variations of flow ducts, located (in their entirety) upstream of the propeller plane, as depicted in Figures B12. Several of the most prevalent, and commercially available are: Mitsui Integrated Ducted Propeller (MIDP), (Ref. B12.a), Hitachi Zosen (HZ) Nozzle, (Ref. B12.b), and Wake Equalizing Duct (ZAD), (Ref. B12.c). The principles of operation are similar for all concepts: reduced flow separation, wake homogenization, reduced propeller loading, and augmented thrust. All concepts claim that forward component of lift generated by the duct profile will be larger than the generated drag (resistance), thus, augmenting propeller thrust. It is also speculated that the ducts can alter the pressure field over the hull afterbody, with a resultant power savings. The ZAD concept also boasts a reduction in rotational losses and increased efficiency due to pre-swirl imparted to the flow by the duct.



(a) (b) (c) (d)

Fig B12. Photographs of flow ducts. (a) MIDP on TAO 168 model, (b) full scale ZAD on full body closed stern, (c) full scale partial ZAD on tunnel stern, and (d), full scale asymmetric ZAD on open shaft and strut propulsion suite

To date, approximately 170 MIDP's have been installed full scale. All ducts have been applied to large block coefficient ships of 43000 to 450000 DWT. Reductions in propeller loading in the range of 3 to as much as 15 percent are claimed, from a variety of sources. A MIDP concept was model scale tested on the US Navy T-AO 168 Class, Figure B12(a). On the T-AO 168 model, an increase in delivered power was measured when the MIDP was installed (Ref. B12.d). In addition, the measured forces on the model MIDP, during the powering experiments, showed that at no speed was it producing a net positive thrust. More than 30 ships have been fitted with an HZ nozzle, (half new constructions and half retrofits), all ships fitted have had block coefficients greater than 0.78. Power savings of up to 12 percent are claimed, from unidentified sources. More than 150 ZAD's have been designed and built for ships of the containership, multi-purpose, and tanker varieties. ZAD type ducts appear to be the most versatile concept, having been applied to full body closed sterns, Figure B12(b), closed tunnel sterns, Figure B12(c), and open shaft and struts, Fig B12(c), alike. The Wake Equalizing Duct (ZAD) concept has been model scale tested on a variety of US Navy ship classes. The AE-36, from Ref. B7.c, (three ZAD designs on a bulbous stern and three ZAD designs on an asymmetric stern) The T-AO 168, from Ref. B12.d, (six ZAD designs). And the T-AGS 38, Ref. B12.e, (four ZAD designs). All of these ZAD designs were tested on each model in a variety of orientations, varying longitudinal location, vertical location, and rotation of the duct in both the yaw and pitch planes. For the AE-36 and the T-AO 168, a total of 12 different model tested ZAD designs, none were found to decrease required delivered power over the baseline propeller without duct. Of the four ZAD designs model tested on the T-AGS 38, only one reduced delivered power by a predicted 1.6 percent. From these US Navy model test experiences, it appears that these concepts are most likely suited to single screw, high block coefficient hullforms, with heavily loaded propellers, not typical of US Navy designs. Therefore, these concepts are not recommended for further consideration under this energy study.

(13) Flow Fins on Hull, Fins to Reduce Bilge Vortex, Grothues (HDF) Spoilers, Profiled Strut Arms, Wake Adapting Fins

Flow fins on hull, fins to reduce bilge vortex, Grothues Spoilers (hydrodynamic fin system or HDF), profiled strut arms, and wake adapting fins, form a similar group of concepts which have adapted some style of fin (or multiple fins) attached to the hull, Figure B13. The purpose of these fins are any of the following: flow re-direction, flow homogenization, reduction of flow separation or induced hull vortices. Some fin designs claim to actually reduce hull resistance by either: reducing the energy lost in the bilge vortices, or by generating on the fins a lift force with a forward component. All tend to be fairly simple devices, which can easily be backfit, and frequently are. Many designs have been model tested world-wide, with predicted power savings in the 0 to 6 percent range. Approximately 30 or more HDF systems have been installed on containerships, bulk carriers, tankers, etc., with claimed power savings of 5 to 11 percent (Ref. B13.a). (However, the accuracy and/or sources of these comparisons are unknown.) They are concepts which are again commercially available, but best suited to single screw, full stern, high block coefficient hullforms, with heavily loaded propellers. Extensive model testing and a full scale installation was conducted by the US Navy on a flow alignment fin for the AO-177 Class (Ref. B13.b). The purpose of this fin, however, was not for energy enhancement, and it consequently showed little to no effect on the full scale ship powering. The flow alignment fin on the AO-177 was successful in the purpose for which it was designed, namely, reducing inboard propeller-excited airborne noise, and propulsor cavitation erosion tendencies. These flow fin concepts are not recommended for further consideration under this energy study.

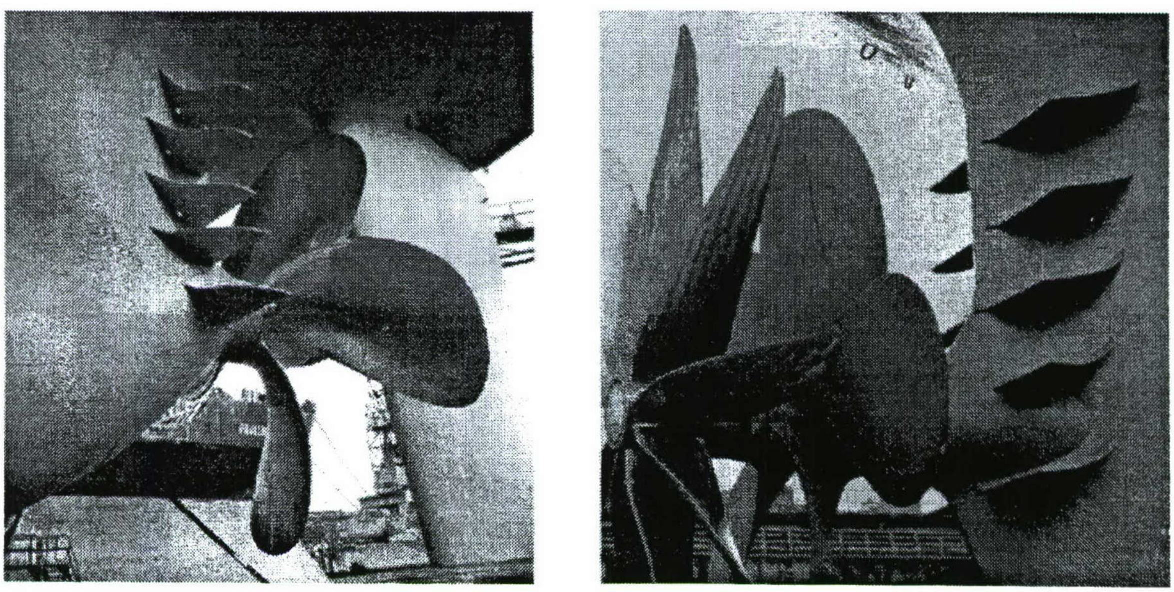
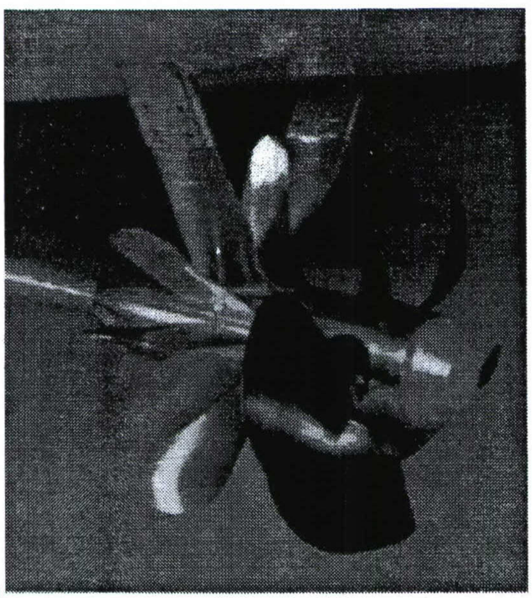
(a)  (b)

Fig B13. Photographs of full scale applications of (a) flow fins on hull, and (b) Grothues Spoilers (note vane wheel installed behind propeller)

(14) Stator Upstream of Propeller, Inflow Control Vanes, Double Guide Fins, Stream Control Installation

These four concepts are all comprised of high aspect ratio fins placed forward of the propeller plane, simply described as stator blades located forward of the propeller. The double guide fins (a pair of fins) and the inflow control vanes, Figure B14(a), (generally three or more fins spaced radialy around the propeller disk), are both concepts designed for open shaft & strut propulsion. The stator upstream of propeller, Figure B14(b), and stream control installation, are designed for closed stern or skeg type hullforms. All concepts work by inducing a pre-rotation of the flow, and/or causing a more circumferentially uniform flow, to be delivered into the propeller. All concepts also attempt to augment forward thrust, by generating on the blades a forward component of lift larger than the induced drag (resistance). Inflow control vanes, referred to as stators, have been designed for US Navy applications with the primary purpose of increased propulsion efficiency, as shown by Neely, et. al. (Ref. B14.a). Applications on models (such as Figure B14.a) have shown that increases in propulsive efficiency of 6-7% could be achieved. The stators model tested to date, however, have shown minimal energy enhancement over the ship's speed range, with the significant power reductions having been realized only near the device's design speed. The data does support the possibility of designing stators with emphasis oriented towards energy enhancement. Additional realizable benefits of the concepts (non-energy issues) are reduced propeller cavitation, noise, and vibrations[2]. The US Navy's interest in inflow control vanes has also been in the reduction of blade erosion, as shown by Smith and Remmers, (Ref. B14.b).

Inflow control vanes are recommended for further consideration. The most promising candidates for study would be the LHD-1, LHA-1, and TAO-187. The concept is most appropriate on the combatant classes, DDG-51, CG-47, DD-963/993, or FFG-7, however, signature considerations may prevail. The stator upstream of propeller device is applicable to the AO-177 Class.

(a) 

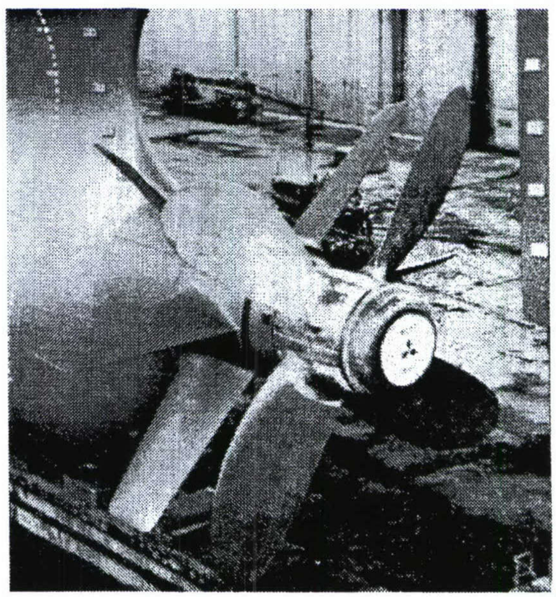
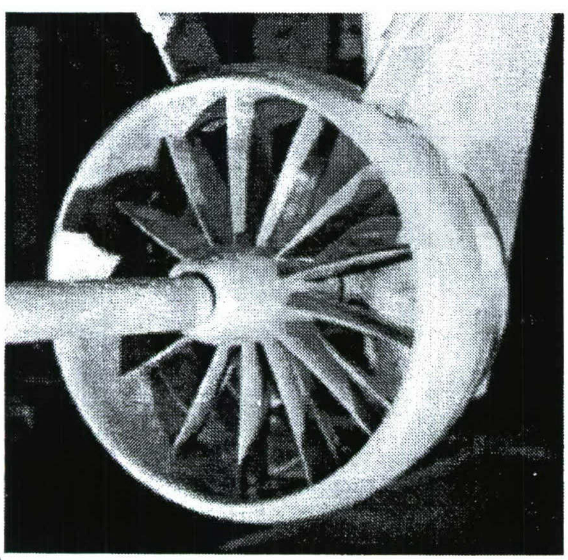
 (b)

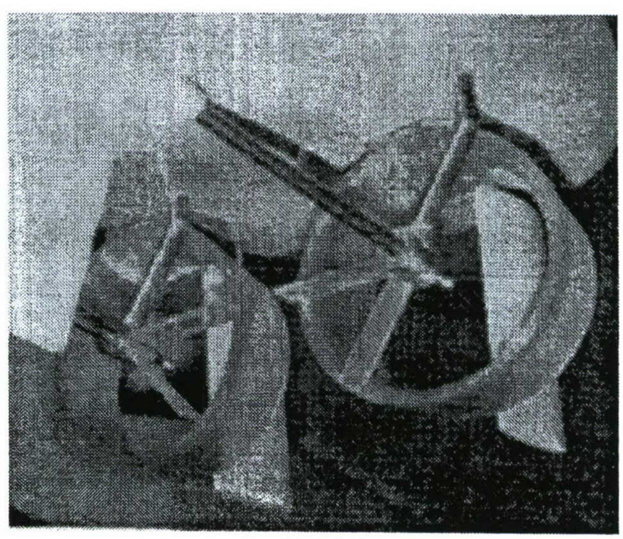
Fig B14. (a) Photograph of inflow control vanes on a US Navy model, and (b) Photograph of full scale stator upstream of propeller

(15) Ducted Inflow Control Vanes, Reaction(tive) Fins (FPHFS)

Both ducted inflow control vanes, Figure B15(a), and reaction(tive) fins, Figure B15(b), combine the previous concepts of an upstream propeller duct and upstream stator blades. The duct/stator is designed as an integrated unit, and located entirety upstream of the propeller plane. The duct/stator operating principals combine the previous two concepts. Design criteria is that the unit induced drag is not larger than the produced forward component of lift. Extensive research into the reaction fin, referred to as Fore-Propeller Hydrodynamical Fin Sector (FPHFS), has been conducted by Marine Design & Research Institute of China (MARIC), (Ref. B15.a). The FPHFS attempts to create a pre-swirl into the propeller so strong as to prevent any rotational flow aft of the propeller. Model tests on two ship designs exhibited up to an 8 percent powering reduction. Two full scale FPHFS applications have been made, on the island pushers *Changjiang* 62025 and *Changjiang* 62027. Claims of full scale power savings for FPHFS of 3 - 7 percent are made based upon sister ship comparison trials. The designers state that FPHFS is most suitable for heavily-loaded propellers, at low speed. US Navy experience is limited to the ducted inflow control vanes on open shafts and struts. Ducted pre-swirl units, such as Figure B15(a), can be designed to operate efficiently, as shown by Hughes and Kinnas (Ref. B15.b). The ducted inflow control vanes, on the US Navy model tests, showed higher delivered power throughout the speed range. Measured forces on the duct/stator unit showing that at no speed was this assembly producing a net positive thrust. Increased propulsor efficiency, however, was measured over the operating speed range, so it may be possible that some performance improvement could be obtained from a new design. Ducted inflow control vanes would be expected to have beneficial energy savings for highly loaded propellers, such as tugs or tankers, for which they have seen limited full scale applications to date. Significant R&D work would be necessary to adapt this technology to US Navy ships. Therefore, while these concepts do profess future possibilities for US Navy applications, most likely in non-energy related areas, they are not recommended here.



(a)



(b)

Fig B15 (a) Photograph of ducted inflow control vanes on US Navy model, and (b) Photograph of FPHFS fins on twin screw Japanese model

(16) Ducted Propeller(s)

Ducted propeller(s), as depicted in Figure B16, are a well recognized, and well accepted, design technology. They are used for generating high amounts of thrust out of a propulsor that is extremely highly loaded, or at/near a zero flow velocity condition, and also in instances where hull draft limitations are severe. Ducted propellers are a common design feature on tugboats, which operate a substantial amount of the time in a bollard pull condition. Ducted propellers have additionally been applied as a means of reducing propeller cavitation and for propeller quieting. It is for these types of non-energy related applications that ducted propellers have been utilized on US Navy surface ship designs[2]. One full scale US Navy surface ship application was that of a pump-jet propulsor[2] on the *USS Glover*, (AGDE-1). Powering performance is of higher classification, however, excessive noise experienced aboard ship, especially during turning maneuvers, was attributed to cavitation on the duct (Ref. B16.a). Ducted propeller systems, while in some applications of the types mentioned above can provide powering reductions, are ordinarily not seen as a means of reducing delivered power for typical US Navy hull designs under normal operational propulsion requirements. Ducted propellers would be expected to have beneficial energy reduction for only ships with very highly loaded propellers. Therefore, ducted propellers are not given further consideration in this energy study.

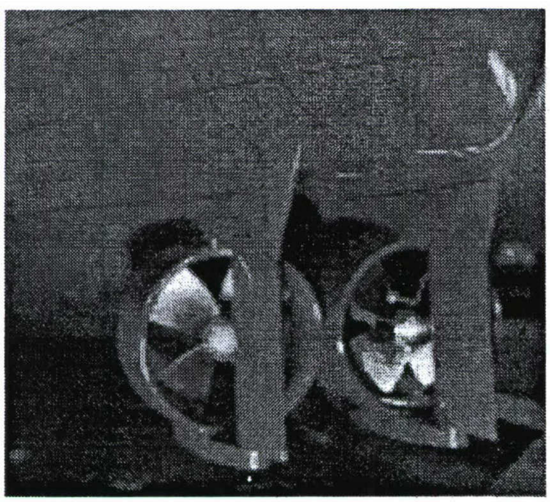
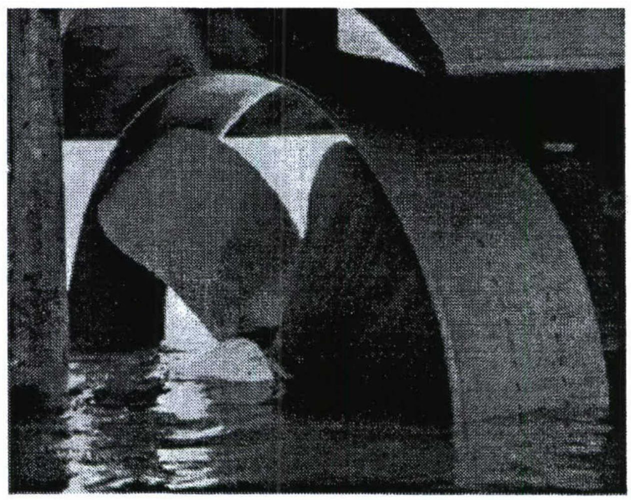
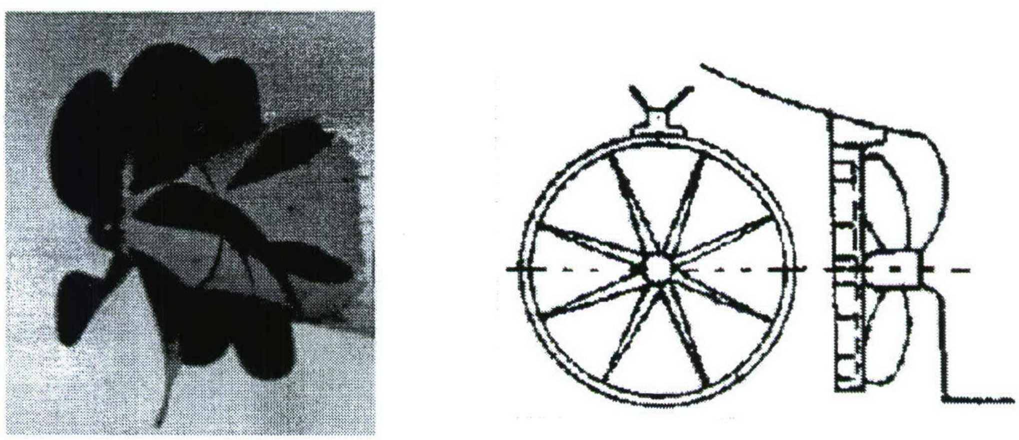
(a)   (b)

Fig B16 (a) Photograph of twin screw ducted propellers on a model, and (b) Photograph of a full scale ducted propeller, in this case a tip vortex free (TVF) propeller

(17) Stator Behind Propeller (Post-Swirl)

The stator behind propeller (or post-swirl) concept, Figures B17, operates on the principal of reducing both the rotational energy losses and axial kinetic energy losses in the propeller slipstream. The efficiency of these devices varies greatly, but significant powering reductions are possible due to increased propulsor efficiencies. Very little operational experience is available in literature for the stator behind propeller used as a backfit device. The US Navy model test experience with stators behind propellers have generally been of the two stage propulsor design. In these cases the philosophy would be to design the propeller with high pitch to minimize viscous losses, but generating some rotational losses, which would be recoverable by the stator as augmented thrust. These two stage propulsors can have high efficiencies in the range of 0.85. A design method for post swirl propulsors was addressed by the US Navy in the PG-100 program, as detailed by Chen (Ref. B17.a). For this application, a post swirl propulsor was designed for a close-to-uniform flow on a tractor pod (Figure B17.a). Emphasis was placed on propulsor efficiency, as well as reduced blade loading and reduced tip circulation, both to insure reduced propeller cavitation characteristics. Model tests conducted by Cusanelli (from Ref. B10.a), insured that the design had reduced the required delivered power of the PG-100. Post-swirl stators may not be applicable to backfitting behind a standard propeller. Recoverable swirl losses for a typical US Navy propeller, on a shaft & strut destroyer, have been estimated to be on the order of only 3 percent. In addition, the backfitting of a stator behind an existing propeller poses serious mechanical difficulties and vibration related concerns. Therefore, at this time, the stator behind propeller concept is not foreseen as a backfittable device, and not considered further in the present energy study. (A related device, stator fins mounted on the rudder or rudder stock, are considered in this report under a separate device group.)

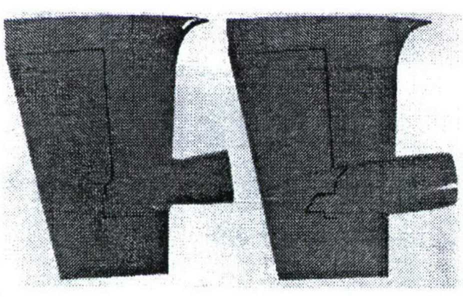


(a) (b)

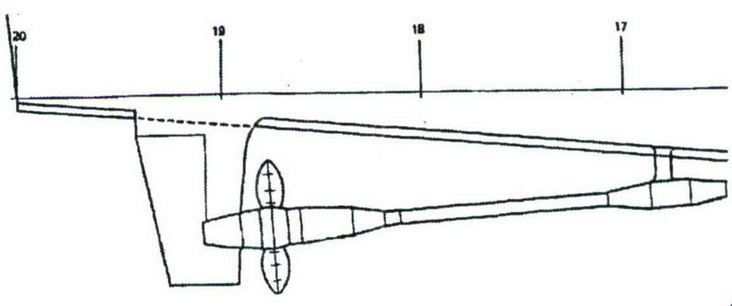
Fig B17 (a) Photograph of model scale post swirl stator behind propeller on a tractor pod, and (b) Sketch of Stator Behind Propeller concept - Japan

(18) Bearing in Rudder Post

The principles of operation, of the propeller shaft bearing in rudder post concept, Figure B18, is the elimination of the propeller shaftline support struts, a reduction of propeller-hub fairwater drag, and augmentation of the recovery of propeller swirl losses. The elimination of support struts reduces the associated shaftline appendage drag. An additional secondary effect of this concept is the elimination of the support strut flow deficits, thus reducing the fluctuations in the wake entering into the propeller plane. The concept has been tried (model scale) on US Navy frigate, destroyer, and cruiser hullforms, (Ref. B18.a). On a single screw frigate configuration model tested, the bearing in rudder post reduced powering by as much as 10 percent. The general conclusion, based on a large number of US Navy model tests, is that the bearing in rudder post is a viable concept with potential for reducing delivered power by 3 percent. The powering reduction stemmed from not only the reduced resistance, but also from increased propeller-hull interaction coefficients and propeller efficiencies, attributed to the cleaner wake, and recovery of propeller losses. There are some technical risks with the concept, primarily associated with structural issues, vibration, rudder cavitation and erosion damage, and shaft support bearings. Because of the developmental nature of bearing designs for the higher power levels necessary for US Navy ships, a long payback period had been estimated in the past, and pursuit of this concept was not continued. It is likely, that with present day bearing design technology, the problems of the point and side loads associated with this concept could be overcome. The US Navy and Coast Guard have operational experience with bearing in rudder post configurations on approximately 200 patrol crafts, (numerous references). These cases do not show any excessive problems with vibration or rudder cavitation. Although the concept on patrol crafts has very limited applicability towards large combatants, due to the significantly lower power levels, it does show proof of the concept. A great many previous model tests indicate that the propeller shaft bearing in rudder post concept is favorable for energy enhancement, and pursuit elsewhere is encouraged. However, this concept is not considered further in the present energy study, because it is strictly a new construction item.



(a)



(b)

Figure B18. Bearing in rudder post concept. (a) Photograph of rudder designs tested on DD-963 model, and (b) sketch of concept on single screw combatant hullform. (Note elimination of struts on main propeller shaft barrel.)

(19) Alternative Main Strut Barrel Designs

Alternative main strut barrel designs are preliminary attempts to achieve a better hydrodynamic shape for the main propeller shaft support strut barrel on open shaft and strut propulsion applications. Some preliminary design sketches are shown in Figure B19. The shape of the main strut barrel has a significant hydrodynamic effect on inflow wake into the propeller, especially near the root area. The barrel shape affects the wake deficit as well as the wake distribution into the propeller. Especially for controllable-pitch propellers, where blade design near the hub has less freedom to adapt to the change of wake due to the restriction that the blade is built to rotate in the hub. For this kind of propeller, the alternative approach to improve propeller efficiency and cavitation performance near the hub area (low propeller radius region) is to provide better inflow wake distribution. The shape of barrel plays an important role to achieve better wake flow near the propeller blade roots. Limited test data that shows that the "cone" shape can yield a preferable wake, (Ref. B19.a). While reduced propeller blade root cavitation and increase cavitation inception speed would be directly realizable by this concept, there are possible benefits to propeller efficiency. As identified in the previous concept, (propeller shaft bearing in rudder post), increased propeller-hull interaction coefficients can be attained due to the cleaner wake provided to the propeller.

It is doubtful that the retrofit of a new strut barrel design would be cost beneficial. The main emphasis of this concept is to provide better inflow wake into the propeller, for reduced blade root cavitation and increased cavitation inception speeds. While the potential for small powering reductions exists, it is felt that the potential for energy reduction would not offset the substantial cost of retrofit. Empirical and CFD work on this concept is in its preliminary stage. Consideration should be given to follow on model test work to verify computational predictions, and to determine energy reduction possibilities. The concept is applicable to all identified US Navy ship classes with open shaft and strut propulsion: CG-47, DD963/993, DDG-51, FFG-7, LPD-17, LHD-1, LHA-1, LSD41&49, TAO-187, and AOE-6.

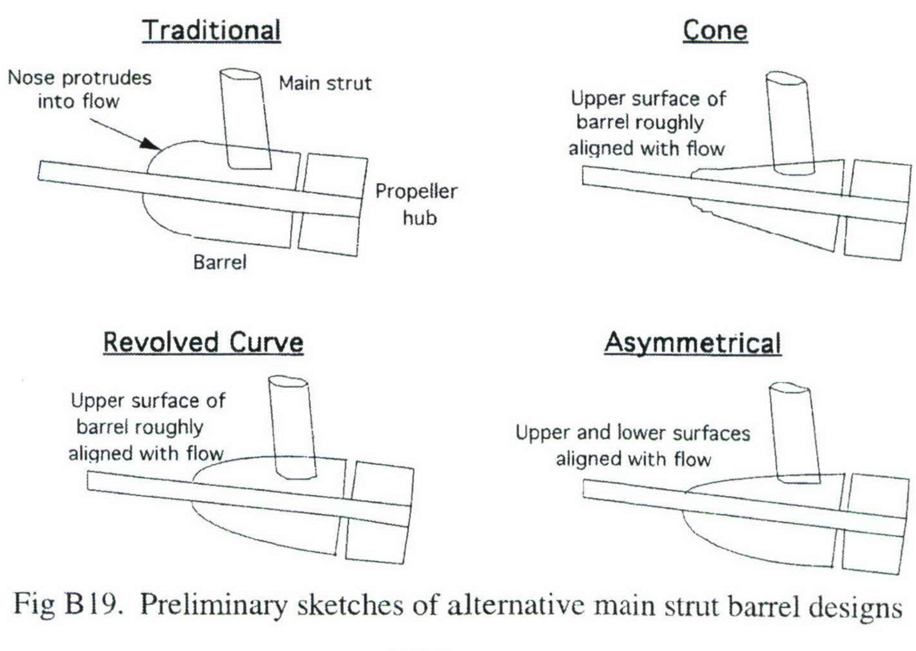
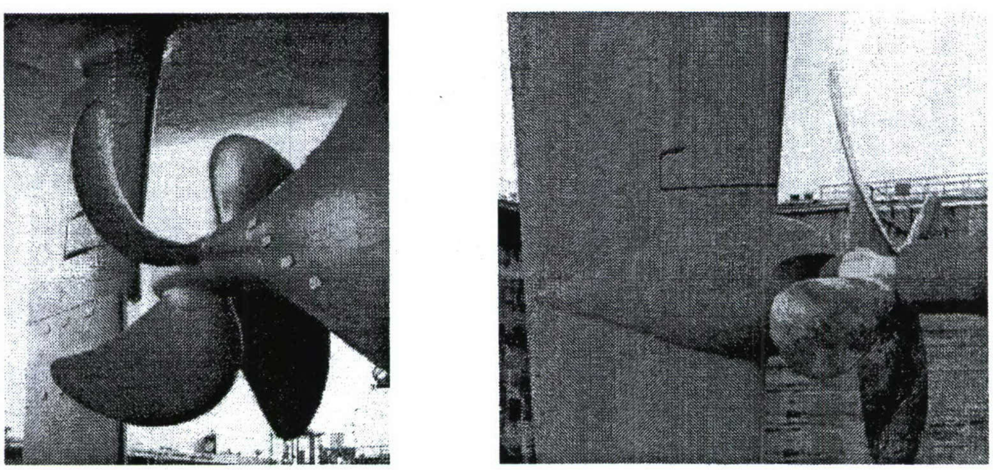


Fig B19. Preliminary sketches of alternative main strut barrel designs

(20) Alternative Rudder Designs, Contra-Guide Rudder, Split Rudder, and Costa Bulb on Rudder

Several alternative rudder designs have been investigated at both full scale and model scale in the past, in an attempt to increase the swirl recovery of a standard rudder. Contra-guide rudder, split rudder, and Costa Bulb on rudder, are a few of the alternative designs. Two of these designs are depicted, full scale, in Figure B20. All designs operate on the principal of regaining lost rotational energy downstream of the propeller. The Costa bulb also acts as an elongated propeller hub, thus reducing excessive hub vortex losses. The rudder devices are generally suitable only to full body ships of the auxiliary or merchant types. For a well designed hull/propulsor system, rotational losses are estimated to be on the order of 7 percent. Much of this rotational energy loss (on the order of 40%) is generally recovered by a well designed rudder placed behind the propeller. Therefore, it is surmised that powering reductions in the range of 1 - 3% are achievable, with some of these alternative rudder designs. Greater energy recovery would be possible only in the wake of an extremely bad hull/propulsor/rudder design, or in the wake of very heavily loaded propellers, not typical of US Navy ships. A powering savings of 1 percent was achieved with a split rudder when evaluated on the Mid-Term Sealift model (from Ref. B3.b).

The ease of ship integration and expected low installation costs, make alternative rudder designs attractive for the present study. The recommendation would be to conduct R&D in parallel with the devices to be introduced in the following group (thrusting fins on rudders). The rudder devices are directly applicable to the AO-177 Class. There is the possibility that some of the alternative rudder designs would be suitable to the open shafts & struts Navy hulls. However, additional R&D work would be necessary to determine their suitability.



(a) (b)

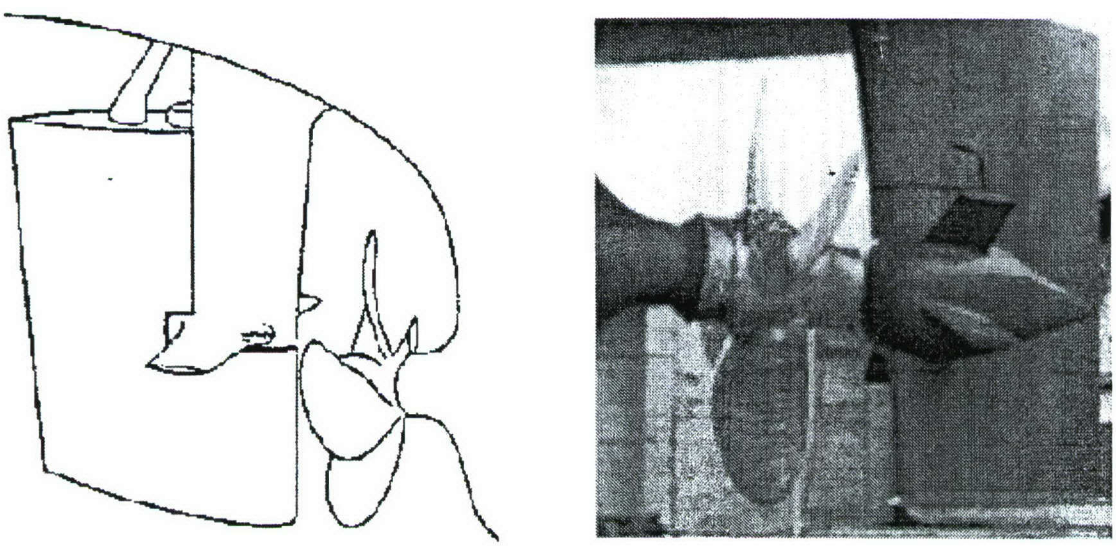
Fig B20. Photographs of full scale alternative rudders (a) split rudder, and (b) Costa Bulb rudder

Effect rudders, an alternative design for small craft, operate with a specific combination of opposing/non-opposing rudder angles, and require a fairly complex steering system which would pose problems for a retrofit. They are not suitable for the ships in this study, and are not included in the recommendation of this device grouping.

(21) Thrusting Fins on Rudder(s), Additional Thrusting (AT) Fins, Profiling Fins on Rudder, Rudder-Bulb-Fins

These devices, the additional thrusting (AT) fin, profiling fins on rudder, and the rudder-bulb-fin, are all comprised of small thrusting fins placed on the rudder and/or rudder post, Figure B21. The rudder-bulb-fin utilizes a rudder (Costa) bulb in combination with fins. All devices operate on the principal of regaining lost rotational energy downstream of the propeller. Approximately 20 full scale applications of these concepts have been produced, however, all applications have been on single screw, full bodied ships of the tanker/bulk carrier type hullforms. A general review of this concept is presented in Ref. B21.a. The efficiency of these devices varies greatly, and powering reductions of as much as 5 percent are claimed. These claims for large energy recovery by these (rudder fin) concepts, it is surmised, would be possible only in the wake of an extremely bad hull/propulsor/rudder design, or in the wake of very heavily loaded propellers. Since neither of these two situations are typical of US Navy ships, more modest powering reductions would only be possible. A powering savings of 3 percent was achieved with relatively small rudder mounted thrusting fins when evaluated on the Mid-Term Sealift model (from Ref. B3.b).

The ease of ship integration and expected low installation costs, make these devices attractive for the present energy study. The recommendation would be to conduct combined R&D for alternative rudder designs with the thrusting fins on the rudder. All the combined alternative rudder design concepts are directly applicable to the AO-177 Class. There is, again, the possibility that some of these alternative rudder designs would be suitable to the open shafts & struts Navy hulls, with some additional R&D study.



(a) (b)

Fig B21 (a) Sketch of additional thrusting (AT) fin, and (b) Photograph of full scale rudder-bulb-fin

(22) Steering Nozzle (Ring Rudder)

The steering nozzle (or ring rudder), Figure B22, is comprised of a shroud surrounding the propeller blades, suspended and rotated on a rudder stock. It is used mainly when expected propeller loading is high, where thrust loading coefficient will exceed 2.0. The concept is similar to the traditional propeller duct (device group 16), however, the propeller tip - to - shroud clearances are designed larger to allow for the steerable feature. The duct design can taper along forward - to - aft diameters, incorporating a nozzle concept. The steering nozzle concept is also reportedly used to increase the ship payload for equivalent length, for propeller protection, and in the case of draft limited vessels. Principal effects are increased wake velocity through the propeller plane, and augmented thrust, both due to specially designed duct section profiles. The steering force is provided by the reaction of the turned propeller race and the shroud lift force. If additional side force is necessary, flaps are sometimes attached to the trailing edge of the shroud. The steering nozzle has been used widely in Europe, mainly on tugs and fishing vessels. Recently a ring rudder concept was tested by the US Navy on the Mid-Term Sealift at model scale (from Ref. B3.b). The ring rudder concept did not reduce powering when compared to the twin rudder parent hullform. However, the design was successful in its intent, i.e., increased hull and propulsive efficiency was achieved. This was a first iteration ring rudder design, on the Mid-Term Sealift model, and did not include specially designed section profiles on the shroud. Therefore, the unit did not provide the thrust augmentation possible with this device. There is really no conclusive data available to the effect that the steering nozzle reduces powering requirements, and it is most suited to ship hullforms not typical of US Navy designs. Therefore, the steering nozzle (ring rudder) device is not recommended for further consideration under this energy study.

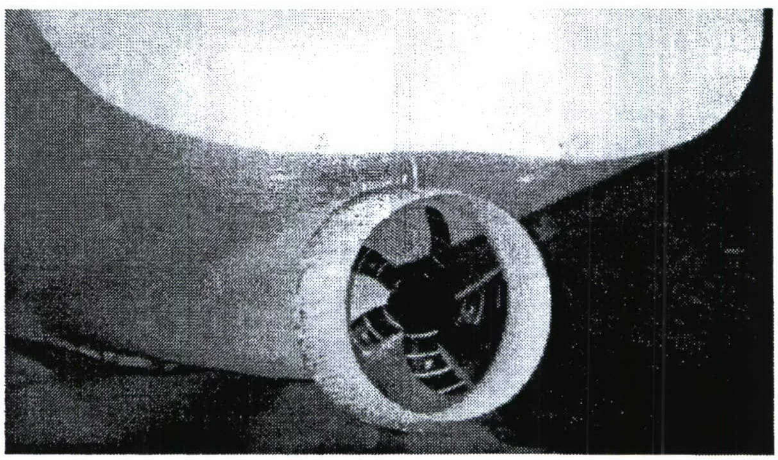


Fig B22. Ring rudder concept on the Mid-Term Sealift model

(23) Semi Tunnel Nozzle, Semi-Duct

The semi tunnel nozzle and the semi-duct, Figure B23, are combinations of previously introduced concepts of stern tunnels (device 5), nozzle or ducts (devices 12 and 15), and flow fins (device 13). A

semi tunnel nozzle consists of a stern design with a very moderate tunnel shape, into which a partial ring nozzle has been faired. A semi-duct is simply a partial ring nozzle, faired into a non-tunnel stern hullform. Both designs most closely resemble a flow alignment fin concept. Both concepts are suitable only on single screw, full bodied hullforms, and are most probably new construction items. Most of the design technology would be covered under different concept headings, and most designs would not be retrofittable, therefore, pursuit of these concepts as a separate category is not recommended in this energy study.

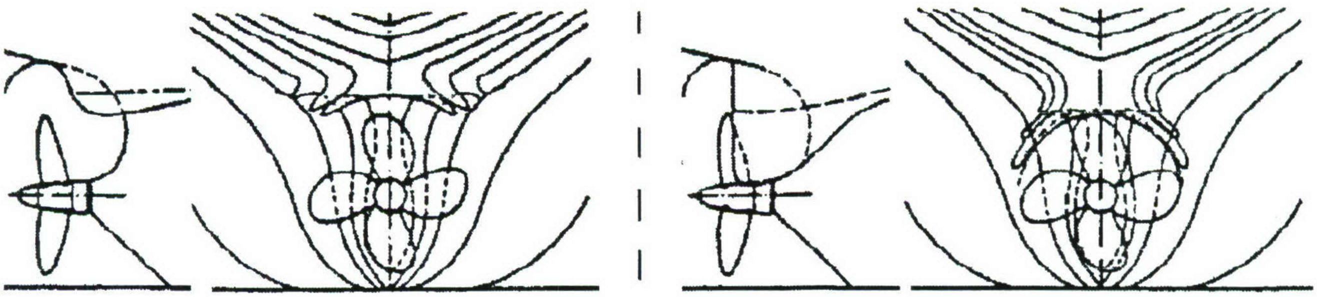


Fig B23. Sketches of examples of semi-tunnel, semi-duct concepts

(24) Propulsion Sterntube

The propulsion sterntube, Figure B24, consists of a large structural tube and associated cowling, which encases and suspends the propeller shaftline. The advantages of this design are the reduction in associated open shaft & strut appendage drag, and the elimination of the two strut flow deficits, thus reducing the fluctuations in the wake entering into the propeller plane. However, the increased diameter of the shafting system preceding the propeller hub, would have a significant effect on the inflow wake into the propeller plane near the root area. A propulsion sterntube was tried (model scale) on the AE-36 (from Ref. B7.c). The results of this application showed a resultant powering reduction of only 0.6 percent, resulting solely from resistance reduction. Increased propulsive, propeller, and/or hull efficiencies were not realized with the propulsion sterntube. Lack of US Navy operational experience, and complexity of calculations/predictions of forces on propulsion sterntube, combine to give this device a large technical risk factor. The propulsion sterntube is not considered further in the present energy study, because it is strictly a new construction item.

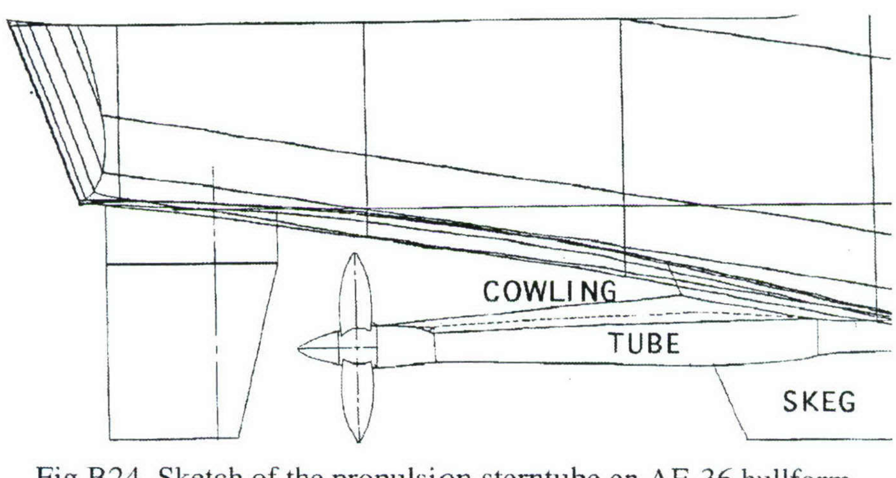
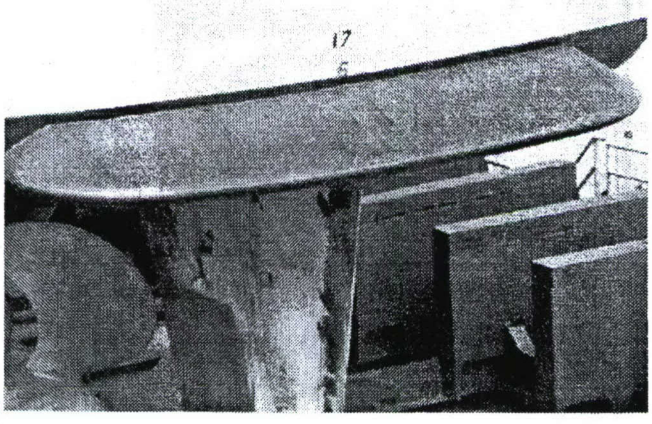


Fig B24. Sketch of the propulsion sterntube on AE-36 hullform

(25) Stern Flap, Stern Wedge

The stern flap, Figure B25, and the stern wedge, are two similar treatments at the transom of combatant type hullforms. They are relatively small devices built of plate fitted to the transom of a ship at an angle relative to the centerline buttock of the ship. A stern flap is an extension of the hull bottom surface aft of the transom, while a stern wedge is fitted to the hull surface beneath the transom. Comprehensive presentations of the effects on US Navy hullforms are given for stern flaps in Ref. B25.a, and for stern wedges in Ref. B25.b. The U.S. Navy has investigated the potential for improved powering performance by the installation of stern flaps and stern wedges on many ship designs. Recently, the emphasis has been placed on stern flap design only, as they have been proven to perform slightly better than wedges in comparative model testing. Powering reductions on the order of 6 to 10 percent at cruise and maximum speeds have been measured model scale and verified full scale. Stern flaps represent a viable mechanism for reducing resistance of ships which operate at speeds of F_N of 0.2 and greater. Some identified physical mechanisms for improved performance due to stern flaps are: effects on the pressure distribution over the afterbody, modification of ship trim and apparent displacement, modification of far field wave energy and localized transom wave system, and increased apparent ship length. The US Navy has retrofitted stern flaps on two FFG-7 Class frigates, and verified full scale performance improvements (Ref. B25.c). Stern flap performance improvements, demonstrated on Patrol Coastal PC-13, has lead to the Navy's decision to retrofit flaps on the entire PC-1 class (Ref. B25.d). An investigation is underway to quantify the energy savings with stern flaps on the DD-963 and CG-47 class ships, and to install a flap on one of these classes in FY97. Stern flaps will be featured on the new LPD-17 and DDG-51 flight 2A ships. Numerous model tests have shown powering benefits with stern flaps on larger, sealift type ships. Construction and retrofitting costs of a stern flap, on a combatant hullform, could be as low as $40,000 per ship, making this concept an extremely low-cost retrofit, which is suited to a great variety of hullforms.

It is recommended that investigations underway be continued, and new investigations be undertaken in this energy study into the merits of stern flap performance potential on all identified US Navy ships.

(a) 

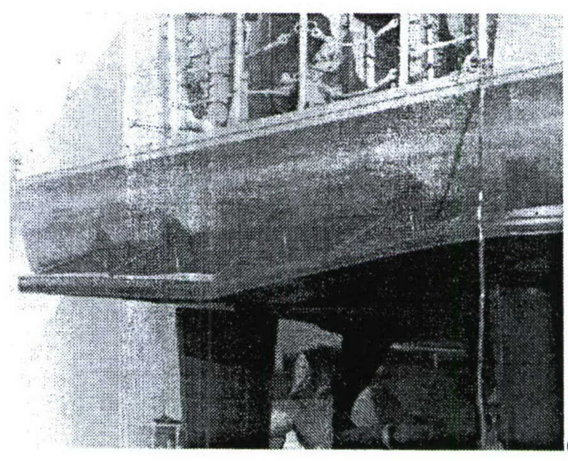
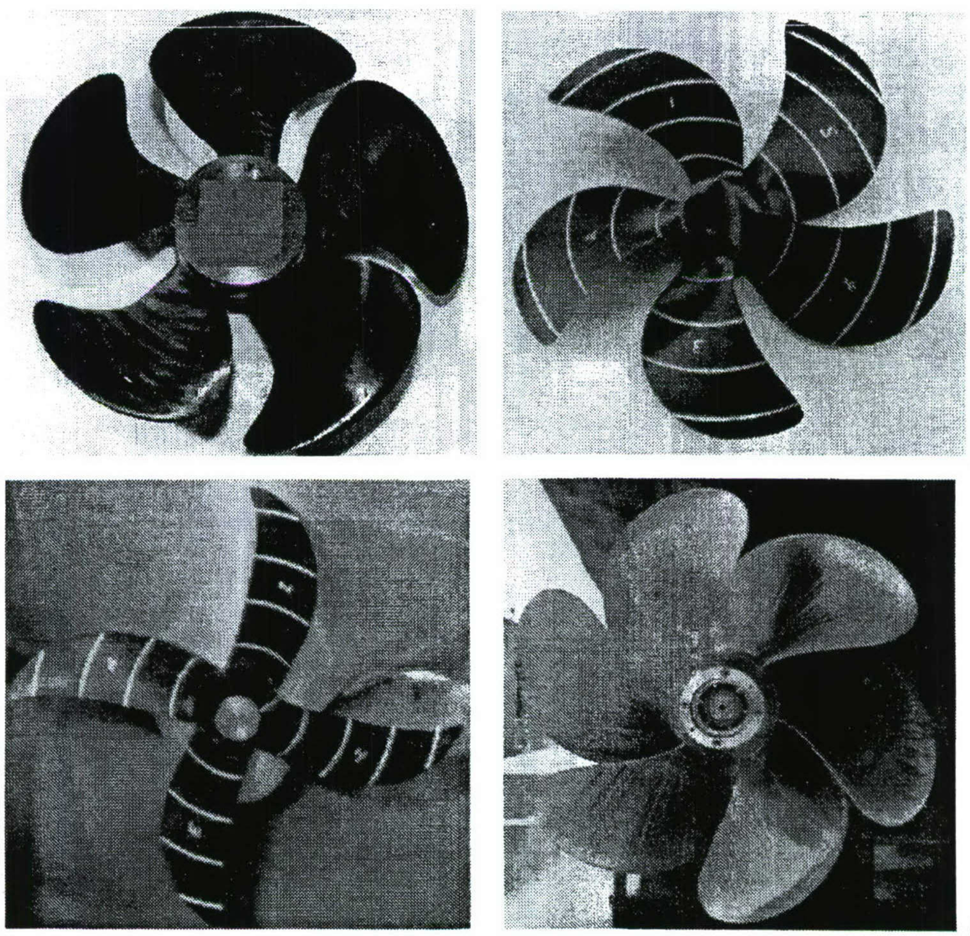
 (b)

Fig B25. Photographs of full scale stern flaps applications. (a) FFG-7 Class, and (b) PC-1 Class

CATEGORY (C) PROPULSOR(s)

(26) New Propeller Design

The concept of a new, more efficient propeller design, is a universal way of reducing powering requirements. A propeller design procedure has been developed by the US Navy, which incorporates new advanced blade section shapes (Ref. B26.a). These new blade sections are applicable to US Navy propeller designs, and are both less prone to cavitation and more efficient. Recent propeller designs using the advanced blade section shapes are pictured in Figure B26. Both the DDG-51 (Ref. B26.b) and the PC-1 (from Ref. B25.d) propeller performances have been verified full scale. The recent advanced blade section propeller designs for the Mid-Term Sealift program achieved an open water efficiency of 0.83 for the twin screw podded hullform, and 0.776 for the single screw extended skeg hullform, Figure B26(c). A previous propeller design study, focusing on US Navy auxiliaries and amphibious ships, concluded that there were several classes that could benefit from a new propeller design (Ref. B26.c), however, most of the ships studied are now near the end of their service life.



(a) (b) (c) (d)

Fig B26. Recent US Navy propeller designs using advanced blade sections. Designed for (a) DDG-51 destroyer (CP) model, (b) LPD-17 amphibious transport dock (FP) model, (c) Mid-Term Sealift (FP) model, and (d) PC-1 patrol coastal (FP) full scale.

The concept of developing a new, more efficient, propeller design is proven technology. Backfitting is possible, however, the design of a new propeller for a Navy vessel is often associated with considerable R&D, construction, and installation costs. The concept is recommended for further consideration, and is applicable to all of the identified candidate US Navy ship classes.

(27) Low RPM / Large Diameter Propellers

The concept of a low RPM / large diameter propeller operates on an old principle that higher propeller efficiency can be achieved through increased diameter and decreased RPM. Decreases in delivered power of 5 to 15 percent have been documented, with increases in propeller efficiency of as much as 40 percent (Ref. B27.a). Commercial design advances in the technology base of high power, low RPM machinery has given this concept many practical propulsion possibilities. The concept is frequently pursued in conjunction with tunnel sterns. Many US Navy energy programs have evaluated the merits of increasing propeller diameters. Two recent applications are: The AE-36 Energy Enhancement Program (from Ref. B3.a) evaluated a standard 22 ft (6.7 m) diameter versus a 26.5 ft (8.1 m) large diameter propeller on an open shaft tunnel stern hullform. The larger diameter propeller provided for a 6.7 percent decrease in delivered power. The Mid-Term Sealift program (from Ref. B3.b) determined that a propeller diameter increase from the 28 ft (8.5 m) to 30.5 ft (9.3 m) on an extended skeg hullform decreased delivered power by 7.5%, and on a producible skeg hullform decreased delivered power by 6.0%. (The 30.5 ft diameter propeller on the producible skeg hullform, however, was unrealistically large.) Many studies are presently underway to determine the validity of the long-standing US Navy practices for minimum propeller blade tip clearances. The results of model tests on the AE-36 large diameter propeller (10% tip clearance) showed pressure excitation levels judged to still be well within the satisfactory range, and the propeller had a low likelihood of producing excessive hull girder vibrations (Ref. B27.b).

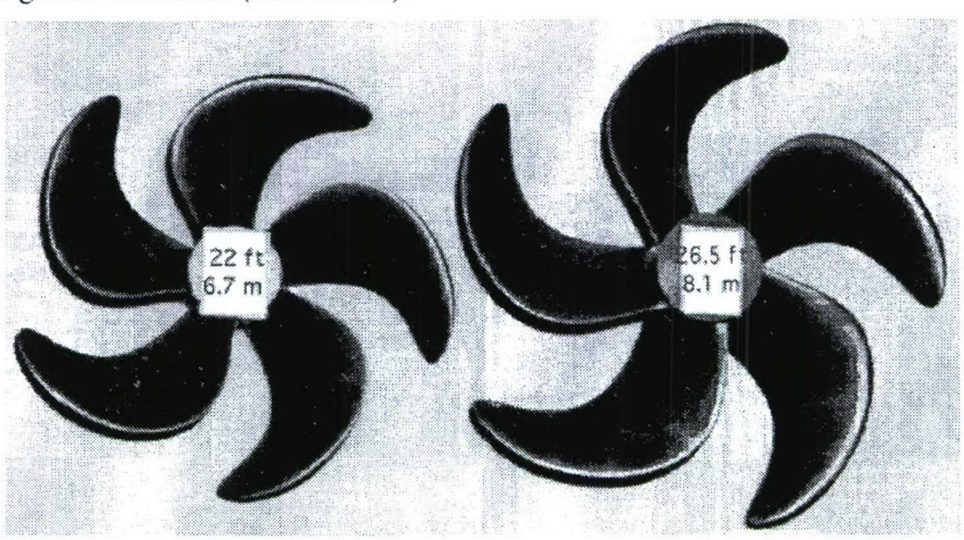


Fig B27. Comparative propellers from AE-36 Energy Enhancement Program
22 ft (6.7 m) diameter, on left, and 26.5 ft (8.1 m) diameter, on right

The concept of a lower RPM, larger diameter, and more efficient propeller design is proven technology. Backfitting is possible, however, the increased diameter of the propeller may decrease propeller tip clearances to marginal or unsatisfactory levels. As a retrofit, the large diameter propeller my be severly limited by the torque and RPM characteristics of the existing ship machinery. As mentioned, R&D, construction, and installation costs, must be taken into account. The concept is recommended for further study, even though a relaxation in current Navy practices for minimum propeller blade tip clearances is not in the foreseeable future. This concept is applicable to all of the US Navy ship classes identified in the energy survey.

(28) Overlapping Propellers

Large diameter overlapping propellers, consist of two propellers placed close to the ship's centerline so that a portion of the inboard sides of the propeller disks are overlapping. One propeller is placed at a longitudinal distance of 0.2 - 0.3 propeller diameters ahead of the second propeller. The concept attempts to meld many of the advantages of other concepts. It combines the higher propeller efficiency associated with large diameter propellers, the reduced propeller loading associated with conventional twin screw propulsion, and reduced resistance over conventional twin screw propulsion. Additional advantages are that the aft propeller may recover some of the forward propeller swirl losses, and there is generally an associated increase in hull efficiency. However, all these advantages may be at the expense of increased cavitation, noise, and vibrations. Model predictions generally indicate improved powering performance of as much as 5 - 15 percent over twin screw, but, in comparison to conventional single screw only small improvements are indicated, (Refs. B28.a, B28.b). There is one full scale application on the *TSSS Sindoro*, Figure B28(a). No comparisons on powering were possible, and the ship propellers suffered heavily from cavitation. However, this was an old design without the benefit of modern propeller design methods.

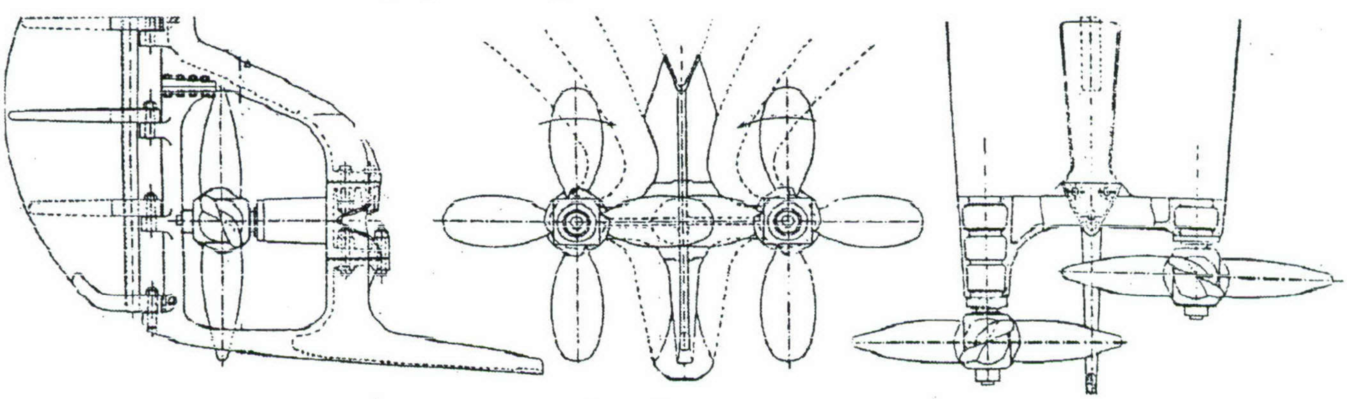


Fig B28(a). Sketch of full scale overlapping propeller arrangement on *TSSS Sindoro*

The large diameter overlapping propellers concept was model tested on the DD-963 destroyer (from Ref. B18.a), Figure B28(b) . The concept showed only a slight powering improvement of 2 percent at high speed, and increased powering at low speeds, versus a twin screw controllable-pitch baseline. Improved propeller design and analysis techniques should allow for improved performance

over this early design, and should also reduce the vibration risks. The fact that this concept is exclusively a new design, however, excludes this concept from further consideration in this energy study.

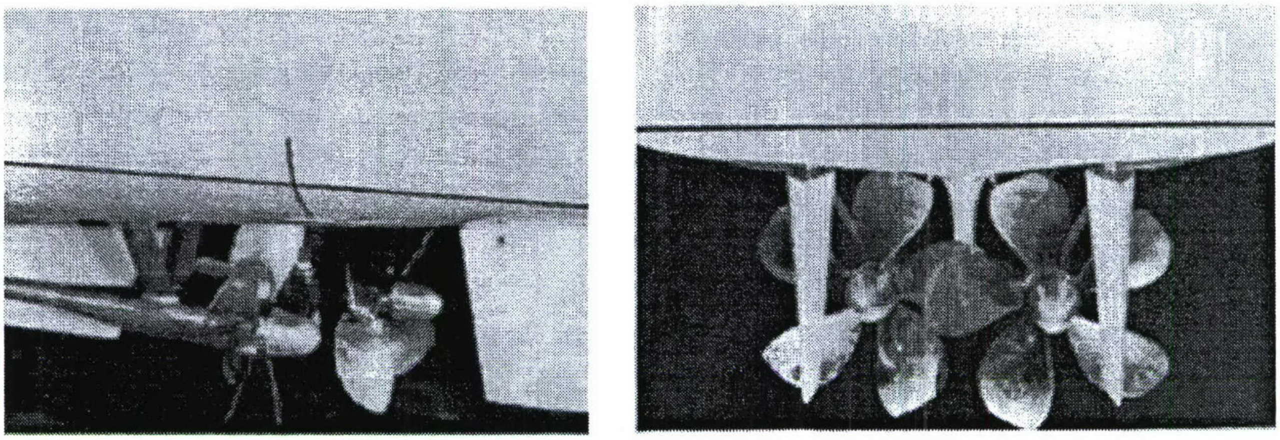


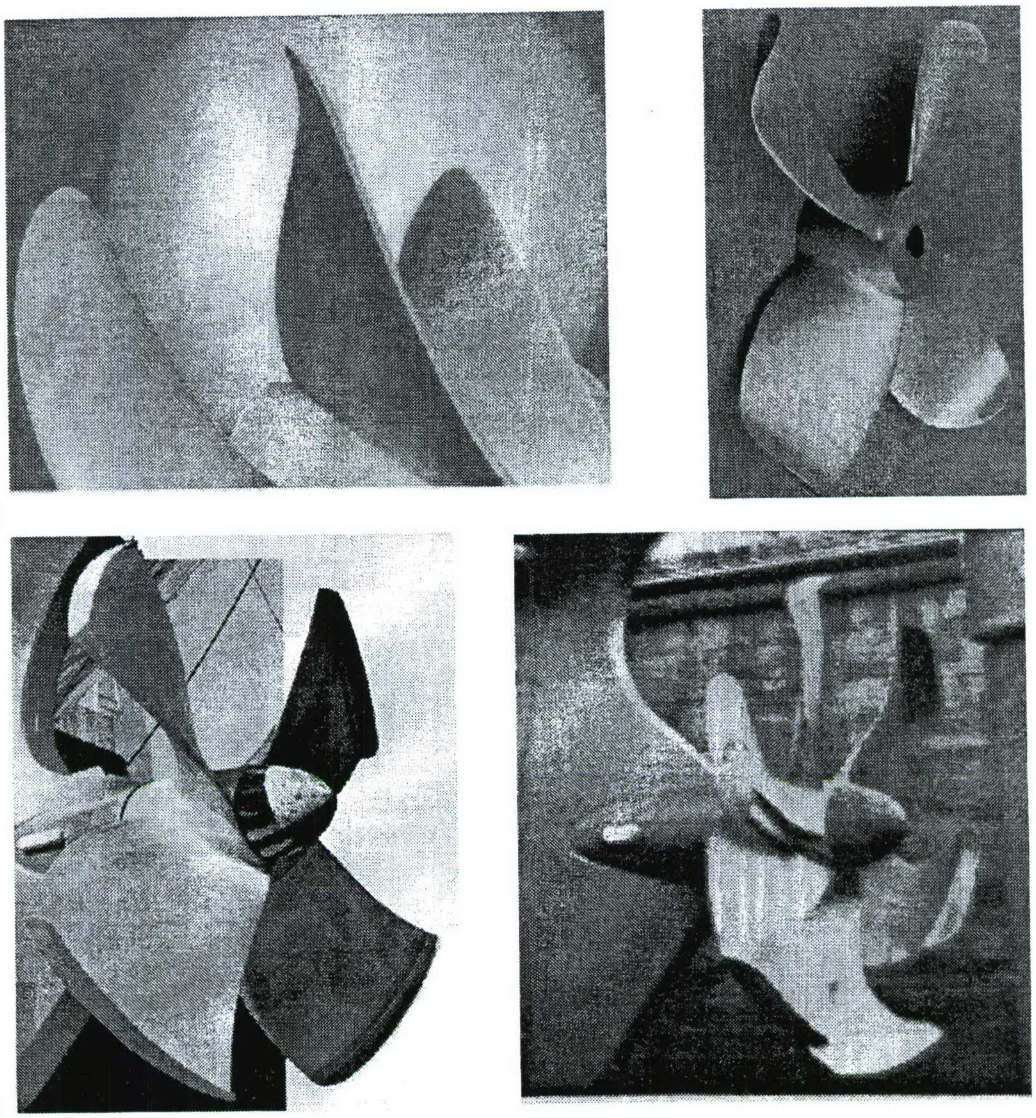
Fig B28(b). Large diameter overlapping propellers on DD-963 model

(29) Energy Efficient Tip Propellers, Kappel propellers, Concentrated Tip Loading (CLT) propellers

Energy Efficient Tip propellers, Kappel propellers, Concentrated Tip Loading (CLT) propellers, and the former generation of CLT called Tip Vortex Free (TVF) propellers, are all forms of propellers which use transitional tip geometry or specialized tip treatments in their blade designs. These propeller blade designs are depicted in Figure B29. The specialized tip geometries are in an attempt to achieve propeller efficiency gains, by way of more heavily loaded blade tips, without suffering excessive cavitation losses. The increases in efficiency may, however, be partially offset by the increased drag of the blade tips. By far the most well known of these propeller concepts is the CLT propeller. More than 120 CLT propellers (including its predecessor TVF propellers) have been fitted, in both fixed pitch and controllable pitch versions, to a vast variety of ship types. Advantages of these propellers as determined full scale are: reduction in fuel consumption of 8 to 12 percent, reduction of cavitation and vibration, improved maneuvering, and increased speed, (Ref. B29.a). The Kappel propeller boasts many of the same advantages, but claims that its curved rake at the blade tips is more easily manufactured, so that the pay-back period is shortened, (Ref. B29.b). Recent US Navy experience, with this type of propeller blade, is through the design of the PC-1 Class propellers, Figure B29(a). The propeller designer stated that the transitional tip geometry permitted loading of the tip, and a slight efficiency gain. The blade tips still retained acceptable cavitation performance, showing very little cavitation on the blade tips at the propeller design point. Full scale trials on the PC-13 confirmed the propeller efficiency gains, but the propellers exhibited slightly greater cavitation patterns on the blade tips than predicted in the model experiments.

The design of specialized propeller blade tip geometries presents a viable means of getting more efficiency out of a propeller without sacrificing cavitation performance. In the case of the CLT, it is a proven mature technology for commercial applications. Backfitting is possible, and therefore, the

concept is recommended for further consideration. These propeller designs could be applicable to all of the US Navy ship classes identified in the energy survey. However, suitability to combatant hullforms is uncertain, and due to this, there is the possibility that significant R&D would be necessary to adapt this technology to US Navy ships.



(a) (b) (c) (d)

Fig B29 Tip treatment propellers: (a) Computer rendering of energy efficient tip propeller, (b) Photograph of model Kappel propeller, (c) Photograph of tip vortex free (TVF) propeller, and (d) Photograph of concentrated tip loaded (CLT) propeller

(30) Contra-Rotating Propellers

Contra-Rotating propellers, Figure B30, are a mature technology, well known for over 80 years as a method of reducing delivered power (Ref. B30.a). The concept consists of two propellers, revolving in opposing directions, placed directly behind one another on a single shaftline. The aft propeller is driven by a shaft which is located inside a hollow shaft which drives the forward propeller. They are suitable for twin or single shaftlines, open or closed sterns. Contra-Rotating propellers operate on the principal of regaining with the aft propeller, the lost rotational energy downstream of the

forward propeller. Design philosophy would be for the forward propeller to be designed with high pitch to minimize viscous losses, but generating some rotational losses, which would be recoverable by aft propeller as pre-swirl into the disk. The efficiency of these complex mechanical systems vary, but significant powering reductions are possible due to increased open water propulsor efficiencies which may be as high as 0.85. Most predictions place the possible powering reductions for contra-rotating propellers in the wide range of 5 to 20 percent. The contra-rotating propeller designs usually have greatly reduced propeller RPMs compared to single rotation. Reduced cavitation, noise, and vibrations can be a direct result of the reduced propeller RPM. Contra-Rotating propellers have seen limited high power or naval applications due to the associated complexity of the mechanical drive systems. However, as a result of five-years technical design studies, Mitsubishi Heavy Industries (MHI) now claims to have developed a large scale contra-rotating propulsion system with sufficient reliability for commercial operations (Ref. B30.b). Four Japanese built large vessel applications of contra-rotating propellers exist. Two of these systems present operational experience for contra-rotating propellers used as a backfit device (Ref. B30.c). For the bulk carrier *Juno*, a delivered power savings of 15 percent was recorded with contra-rotating propellers. Two of these ships, MHI's 258000 dwt (26700 hP) *Cosmo Delphinus*, and Idemitsu Tanker Co.'s (24500 hP) *Okinoshima Maru*, are examples of purpose-built ships constructed with contra-rotating propellers, Figures B30(a) and B30(b). For the *Maru*, a 14 percent power savings is claimed.

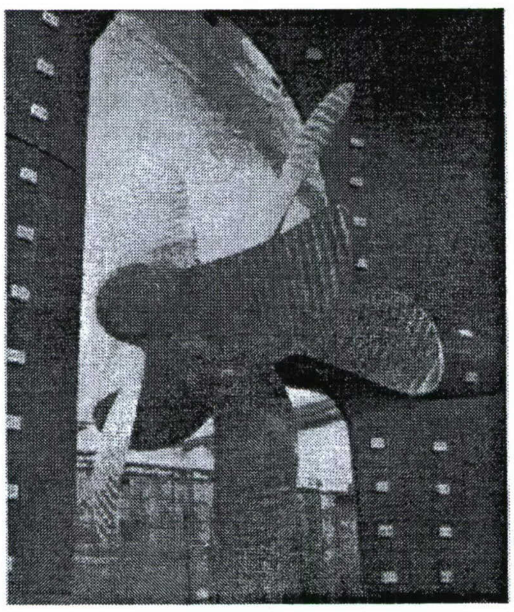
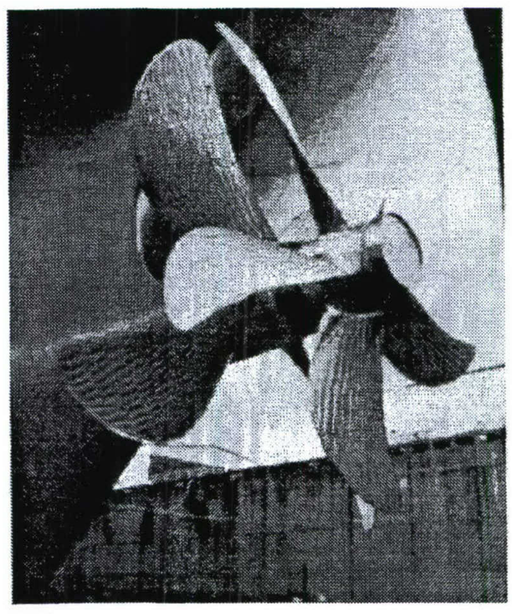
(a)   (b)

Fig B30. Photographs of full scale applications of contra-rotating propellers on two Japanese VLCCs. (a) MHI's *Cosmo Delphinus*, and (b) Idemitsu Tanker Co.'s *Okinoshima Maru*

The US Navy has model tested contra-rotating propellers on a variety of ship hullforms. The most recent applications are on the DDG-51 (Ref B30.d), Figure B30(c), and the Mid-Term Sealift (from Ref. B3.b). The contra-rotating propellers on the DDG-51 reduced the delivered power 10.5 percent at the design speed, and 7.6 percent overall across the speed range. On the Mid-Term Sealift, single shaftline contra-rotating propellers also resulted in a delivered power decrease of 10 percent. The

significant achievable delivered power reductions and improved warfighting capabilities of contra-rotating propellers continue to make this an attractive technology for study in other arenas. When considered in conjunction with podded hullforms and electric drive, contra-rotating propellers become an important element of a long-term developmental effort to support future combatant propulsion system design. For US Navy applications, this concept would be exclusively a new design, and therefore, is not a candidate for further consideration in this study.

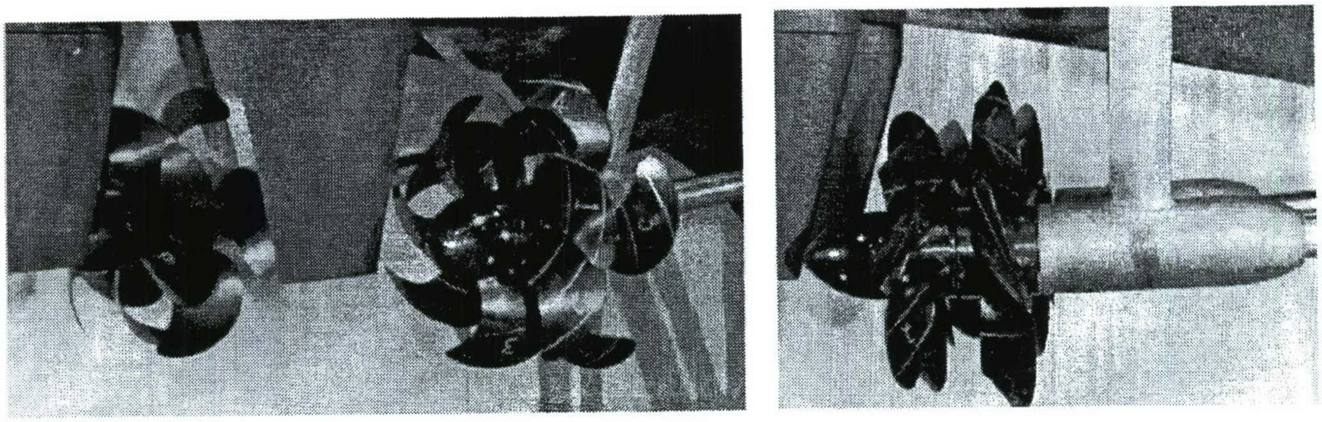


Fig B30(c). Photographs of twin shaftline contra-rotating propellers on DDG-51 model

(31) Tandem Propellers

Tandem propellers are a compound propulsor concept consisting of two fixed pitch propellers, revolving in the same direction on a single shaftline, placed directly behind one another, Figure B31. The forward and aft propellers have comparable diameter and equal number of blades. The propeller blade rows are offset circumferentially on the shaft so that the forward blades do not shadow the aft blades. The main intent of the tandem propellers concept is to satisfy stringent acoustic requirements with a system of fairly simple mechanical complexity. However, the concept can achieve propeller efficiency gains, by way of reducing propeller RPM, blade loading, and blade chord length (high aspect ratio foils), while maintaining or increasing total blade area. They are suitable for twin or single shaftlines, open or closed sterns. The US Navy model tested tandem propellers on the DD-963, Figure B31.

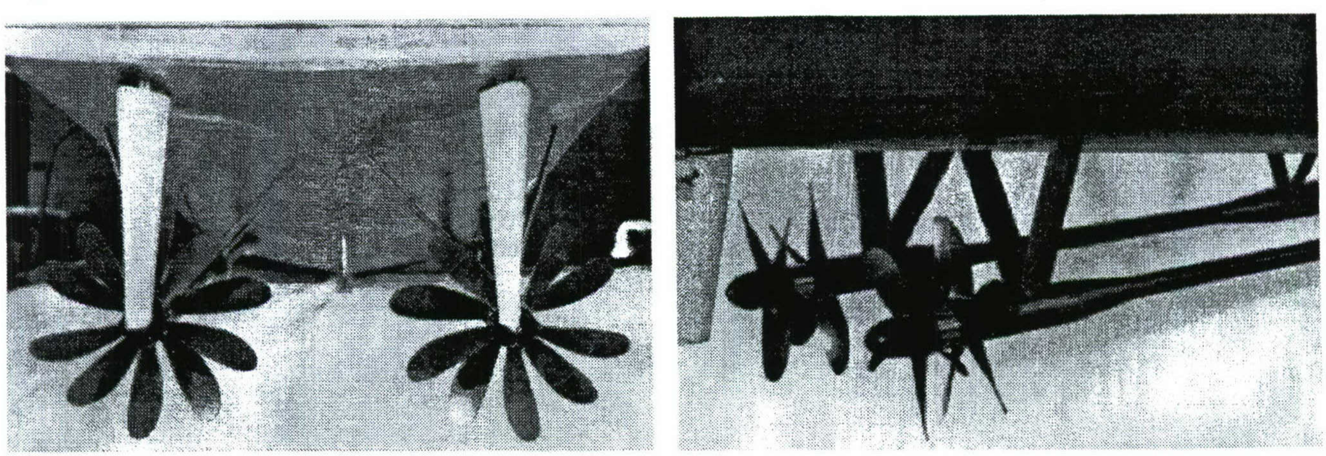


Fig B31. Photographs of tandem propellers on DD-963 model

This model experience on the DD-963 (from Ref. B18.a), showed that the tandem propellers generally had about the same efficiency of a single fixed-pitch propeller of the same diameter. It was determined that the drawback of the tandem propellers concept was that of difficulties in designing matched propellers that performed as desired. It is surmised, that satisfactory tandem propeller performance could be achieved, though significant R&D would be necessary to achieve the desired performance. Suitability as a retrofit device is uncertain, the weight of the second propeller may easily exceed the design limits of the existing shafting, bearings, or struts, thus making retrofit extremely costly or impossible. Therefore, the tandem propellers concept is not recommended for further evaluation in this energy study.

(32) Propeller Fairwater Designs

Propeller fairwaters are simply treatments to the termination of the propeller hub. They can be flat sided, rounded, elliptical, etc., or a truncated form of any of these, Figure B32(a). The fairwater is generally tapered aft of the propeller hub, but in some cases, may actually expend from the propeller hub diameter. The fairwaters can effect propeller efficiency by elongating the propeller hub, preventing flow separation and excessive vorticity. The fairwater can also have an effect on the streamlines aft of the propeller, affecting rotational losses by imparting the rotation to the flow at an altered diameter. The fairwater can also have a pronounced effect on propeller hub vortex cavitation.

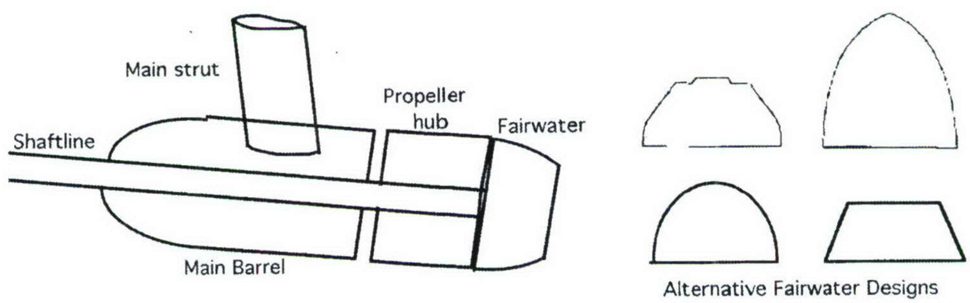


Fig B32(a) Sketch depicting propeller fairwaters concept and example alternative fairwater designs

The US Navy investigated the effects on resistance and powering of variations in fairwater designs on the DD-963 destroyer (Ref. B32.a), Figure B32(b). The DD-963 model, when fitted with either of fairwaters "B" or "C" (in photograph), required roughly 1.0 percent less delivered power than with the fleet design fairwater "A" in the photograph.

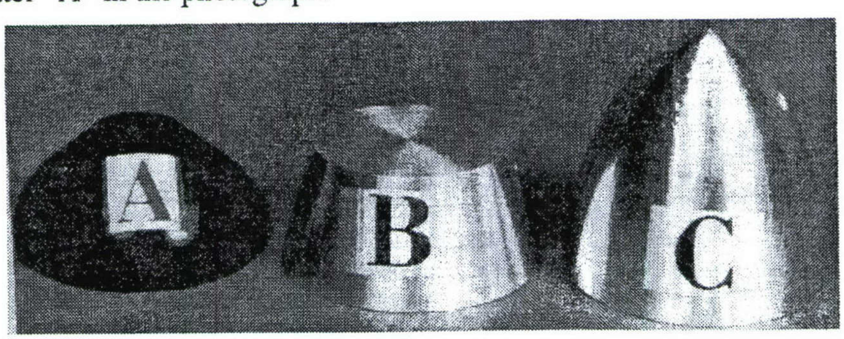


Fig B32(b) Photograph of alternative fairwater designs tested on DD-963 model

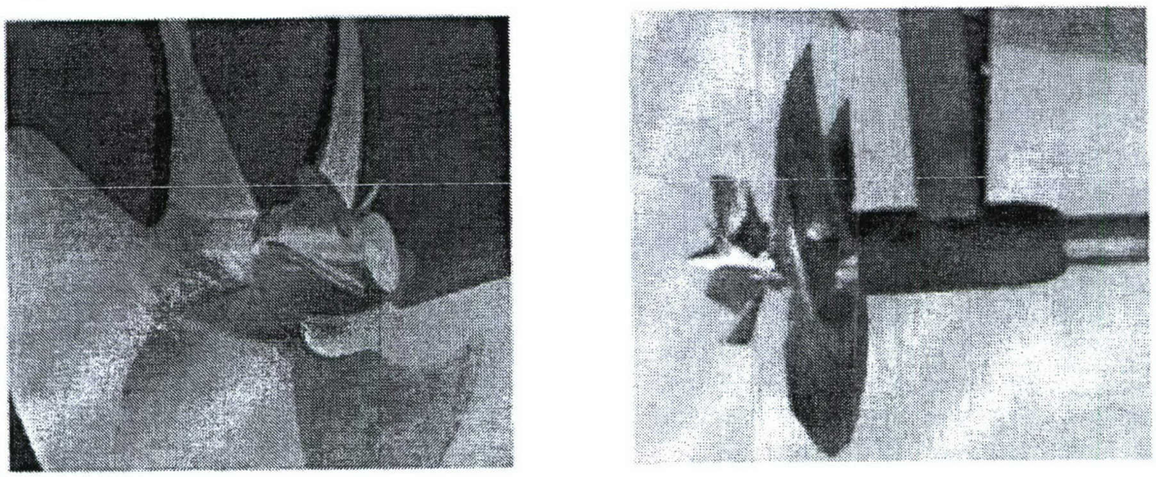
The effect of adding a flat sided, tapered and truncated, fairwater to the propeller hub of the PC-1 Class, (existing design did not include a fairwater), was investigated at both model and full scale. The model tests were inconclusive. The full scale trials concluded that there was a slight decrease in delivered power with the fairwaters installed. Full scale trials on PC-1 Class were also conducted with a flat sided fairwater that expanded aft of the propeller hub. This expended fairwater caused delivered power to increase through all of the speed range with the exception of the extreme high end. Near full engine power levels, a decrease in delivered power, and an increase in ship speed was recorded. It is believed that the expanded fairwater retarded propeller cavitation in the inner half of the propeller disk. Thus, thrust breakdown losses were reduced, thereby providing for the high end power improvement.

The ease of ship integration and expected low installation costs, make some of the alternative fairwater concepts attractive for the present energy study. The recommendation would be to conduct R&D in parallel with studies into the main strut barrel designs (energy savings device 19), effects on propeller root and hub cavitation, as well as energy enhancement. Alternative fairwater concepts are applicable to all of the US Navy ship classes identified in the energy survey.

(33) Fins (Blades) on Propeller Hub, Propeller Boss Cap Fin (PBCF), Post Swirl Cap (PSC)

Propeller boss cap fin (PBCF), and post swirl cap (PSC), are devices, consisting of a number of small fins or blades, fitted to the propeller fairwater. The device, which rotates with equal RPM to that of the propeller, attempts to recover the rotational energy shed by the propeller. Any increase in propeller efficiency may be partially offset by the increased torque associated with the addition of the blades on the propeller fairwater. Mitsui claims sales of over 200 propeller boss cap fin (PBCF) devices, Figure B33(a). Mitsui promotional literature reports the following effects: A savings in fuel consumption of 3 to 5 percent, a speed increase of 1 to 2 percent, reduction in propeller torque of 1 to 2 percent, and reductions in vibration due to the elimination of hub vortex cavitation. Full scale trials were carried out by Mitsui on two sister ships, the *Mercury Ace* with a PBCF installed and the *Neptune Ace* without PBCF (Ref. B33.a). Efficiency improvements from this pair of PBCF trials of 4 percent were claimed, with an associated speed increase of 0.2 knots. As stated previously, there is always some degree of unreliability in sister ship comparisons. More importantly, however, it is judged that the effectiveness of this type of device depends to a large extent on the details of the propeller design, especially in the blade root area, and the amount of propeller rotational losses. A assessment of the PBCF was prepared by Gearhart and McBride (Ref.B33.b), who concluded that the performance gains were valid. A similar device, the post swirl cap (PSC), Figure B33(b), was model tested by the US Navy during the AE-36 Energy Enhancement Program (from Ref. B3.a). The results of this application showed an increase in the annual propulsion energy when the PSC was installed, mainly due to delivered power increases in the lower half of the speed range. However, the device did provide for savings at the high end of the speed range and a slight increase in maximum speed of 0.1 knots.

The concept of putting blades on the propeller hub/fairwater is easily retrofittable, and could be physically installed, on all US Navy ship classes identified in the energy study. It is unknown whether the concepts of this group would fare well only in the wake of a heavily loaded propeller, or a propeller design with an excessive amount of hub vortex losses. It is assumed that the greatest improvement would be for ships with commercially designed propellers such as the TAO-187. This concept is recommended for further consideration in this energy study, due to its expected low associated costs of ship integration and installation, and (commercially) proven cost benefits. Recommendations would be to retrofit a suitable, commercially available, propeller boss cap fin on the TAO-187 first, and if successful, retrofits on AO-177 and AOE-6. Consideration should be given for retrofit to the amphibians LPD-17, LHD-1, LHA-1, and LSD-41&49, prior to conducting R&D into suitability for eventual retrofit on a combatant.



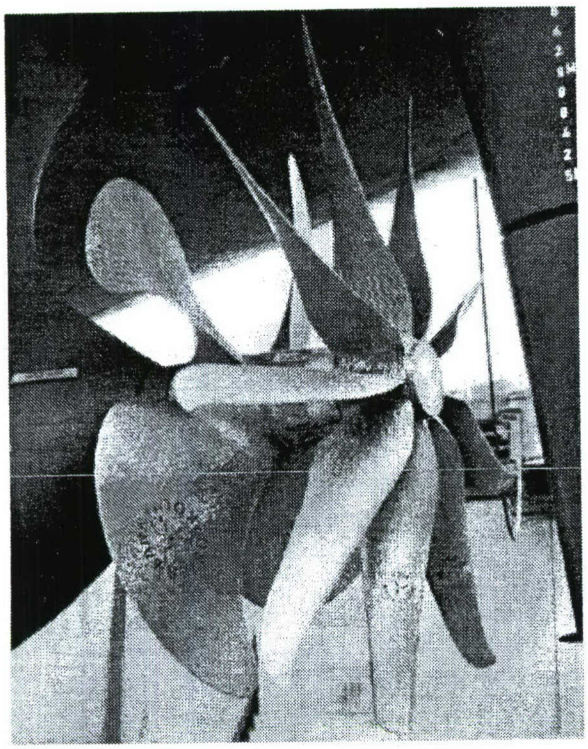
(a) (b)

Fig B33 (a) Image of full scale Propeller Boss Cap Fin (PBCF) from Mitsui literature, and (b) Photograph of Post Swirl Cap (PSC) on AE-36 model

(34) Vane (Grim) Wheel

Vane (Grim) Wheel, Figure 34, is a freely rotating device installed on the propeller shaft, approximately 0.125 propeller diameters downstream of the propeller (Ref. B34.a). The diameter of the vane wheel is larger than that of the propeller, and usually consists of 9 to 12 blades. The chord lengths of the vane wheel's blades are small compared to that of the propeller. Each blade performs two separate functions. The inner part of the vane wheel, the blade root out to roughly the propeller slip stream diameter, acts as a turbine. The outer portion acts as a propeller. The blades are strongly twisted in the transition region between the turbine and the propeller. The vane wheel rotates freely in the same direction as the propeller, but at a much reduced rotational speed in the range of 30 to 50 percent of the propeller RPM. The vane wheel's function is to transform both rotational and axial losses in the propeller slipstream into additional forward thrust. A vane wheel can only be installed if sufficient space is available. Over 50 full scale applications of vane wheels are on record, for a variety of vessels, both as retrofits and as part of two-stage design propulsors. Most applications have been on single screw, full stern hullforms. According to discussions with the inventor, O. Grim, the vane

wheel is most effective on ships where the propeller is not a hydrodynamically optimal. Such a propeller would have high RPM and/or small diameter, which allows the use of inexpensive direct drive diesel propulsion machinery. Delivered power savings of 5 to 12 percent are claimed for single screw vessels with relatively heavily loaded propellers. The delivered power claims appear be realistic, as full scale data supports recorded savings in the range of 2 to 9 percent.



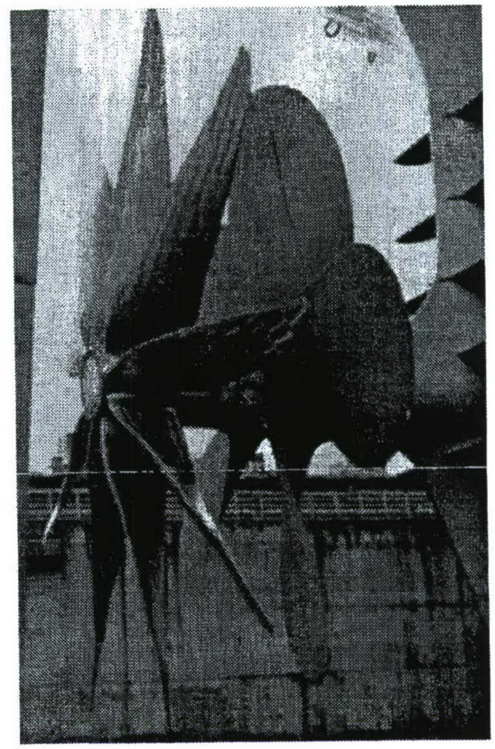


Fig B34. Photographs of two full scale installations of Vane (Grim) Wheels

It is difficult to assess at model scale the energy savings associated with vane wheels. Model scale tests are thought to be subject to severe scale effects. The slow rotational speed, coupled with very short blade chord lengths, consequently make the model scale Reynolds numbers on the vane wheel blades approximately 10 times smaller than those on the propeller blades. To date, only one known publication reports at model scale a measured reduction in power associated with the installation of a vane wheel behind a model propeller, (Ref. B34.b). It appears from the literature, that vane wheels are best suited to single screw hullforms, with heavily loaded propellers, and most likely high block coefficient hulls. This is, of course, is not typical of US Navy designs. Durability and reliability of vane wheels are somewhat questionable, as there are several incidences where blades have been reported damaged or missing, and in worst cases, entire vane wheels have separated from the shaftline. The vane wheel is not considered applicable to open shaft and strut type arrangements on US Navy ships. The increased weight and shafting forces, due to the vane wheel, would likely require increased shafting support strut strength, and therefore, require design modification of the entire propulsion arrangement. The only foreseeable application for the vane wheel on a selected US Navy hullform, would be on the AO-177. However, an earlier study concluded that the required

clearances for a vane wheel did not exist on the AO-177. For the aforementioned reasons, vane (Grim) wheels are not recommended for further consideration under this energy study.

(35) Propeller Pitch Scheduling

Propeller pitch scheduling is an at-sea practice, rather than a device, of setting and maintaining the optimal propeller pitch for minimal engine fuel consumption. This practice is, of course, applicable to only those ships which employ a controllable-pitch propeller or propellers for their main propulsion. The delivered power savings is probably greatest for ships whose prime mover is a gas turbine engine. Gas turbines have a high specific fuel consumption, particularly at partial load operations. For ship speeds of 20 knots and below, considerable fuel savings (as much as 20 percent) has been demonstrated, over a great many years, by operating these ships in a "trailed shaft" mode. In the trailed shaft mode, the ship is driven by one gas turbine and one propeller, while the other propeller is allowed to freely rotate or "windmill". In practice the windmilling propeller is set at maximum ahead pitch. The pitch setting on the driving propeller, however, has been the topic of the pitch scheduling in the past. Model experiments coupled with propulsion systems analysis, on the DD-963 Class, indicated that setting the driving propeller at a pitch less than 100% ahead, could result in a 2 to 4 percent additional savings. The reduced pitch allows the driving gas turbine to operate at a higher RPM, thus reducing its specific fuel consumption. Although the propeller efficiency generally decreases with the reduced pitch, the analysis indicated that the increased engine efficiency would offset this, and a more favorable fuel rate would result. The US Navy conducted full scale trials on the *USS Spruance* (DD-963) to evaluate the effects of pitch scheduling during trailed shaft operations (Ref. B35.a). Analysis of the trials data revealed that a fuel savings of 1 to 2 percent could be achieved in the portion of the speed range between 15 to 20 knots. Recent surveys do indicate that the trailed shaft model is used by many, if not most, of the ship captains. But it is unknown at this time, to what extent pitch scheduling, on the driving propeller, is practiced already by ship captains. Extending pitch scheduling practices into standard operational profiles, such as two screw powering with two-to-four gas turbines on line, has not been thoroughly analyzed. Another approach to pitch scheduling, is to purchase or develop a real time feedback system. This system would automatically optimize the combination of propeller pitch and engine RPM, for minimum fuel consumption. A survey should be conducted to determine what commercial systems are available today, and to see if they are adequate for U.S. Navy use. The principal of optimization would be to minimize fuel flow at an operator specified ship speed, by varying propeller pitch and thus engine RPM. Both software algorithms, and accurate hardware such as thrust and torque meters, fuel flow meters, wind indicators, and ship motion sensors, might be needed. Difficulties with traditional approachs to propeller pitch indicator accuracy, as discussed by Klitsch et. al. (Ref. B35.b), may be avoided because actual sensing of the propeller pitch may not be critical to the system. Such a system could be readily adapted to other desirable modes of operation, including optimization for minimum propeller noise, maximum ship speed, and maximum acceleration. The real-time nature of the system would automatically

account for the effects of hull and propeller fouling, and the normal wear related degradation of engine performance. To a lesser extent, the development of simple, concise, instruction manual, could provide ship captains with the information necessary to make the practice of pitch scheduling a fundamental.

The ease of ship integration and expected low implementation costs, makes the practice of pitch scheduling attractive for the present energy study. The recommendation would be to conduct R&D in parallel with studies into the effects on trailed shaft operations as well as standard operational engine profiles. The practicality of a feedback control system, either developed or purchased commercially, should be studied. The practice of pitch scheduling is applicable to all of the US Navy ship classes identified in the energy survey whose propulsion is by controllable-pitch propeller(s). This includes: CG-47, DD963/993, DDG-51, FFG-7, LSD-41&49, and TAO-187.

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PUBLISHER:

Page Num: | **Vol.:** | **Date Published:** May 1988

Report Num: | **Classification:** | **Ship Type:** | **Reference Type:**

Title: A Practical Design for Contrarotating Propeller Systems

Author(s) Name: Fujino, R., N. Noguchi, S. Ishida, and S. Nishiyama

Keywords: Contra-Rotating Propellers

BOOK: Technical Papers

PUBLISHER: Ishikawajima-Harima Heavy Industries Co. Ltd.

Page Num: | **Vol.:** | **Date Published:**

Report Num: | **Classification:** | **Ship Type:** 8 - Cargo/Auxiliaries | **Reference Type:**

Title: Development of Contrarotating-Propeller System for Juno - a 37,000-DWT Class Bulk Carrier

Author(s) Name: Nishiyama, S., Y. Sákamoto, S. Ishida, R. Fujino, and M. Oshima

Keywords: Contra-Rotating Propellers

BOOK: SNAME Transactions

PUBLISHER: Ishikawajiama-Harima Heavy Industries Co., Ltd.

Page Num: | **Vol.:** 98 | **Date Published:** 1990

Report Num: | **Classification:** | **Ship Type:** | **Reference Type:**

Title: A Practical Design Procedure for Contrarotating Propellers

Author(s) Name: Ishida, S. I., and R. Fujino

Keywords: Contra-Rotating Propellers

BOOK: Technical Papers

PUBLISHER: Ishikawajima-Harima Heavy Industries Co. Ltd.

Page Num: | **Vol.:** | **Date Published:**

Report Num: | **Classification:** | **Ship Type:** | **Reference Type:**

Title: Advanced Propulsion Through Counter Rotating Propellers

Author(s) Name: van Beek, T., and H. de Jong

Keywords: Contra-Rotating Propellers

BOOK: 5th International Marine Design Conference

PUBLISHER:

Page Num: | **Vol.:** | **Date Published:** May 1994

Report Num: | **Classification:** UNCL | **Ship Type:** | **Reference Type:** Technical Report

Title: Integrated Ducted Propulsor Concept

Author(s) Name: Chen, B.Y-H., F. Peterson, and D. T. Valentine

Keywords: Duct Upstream of Propeller; Integrated Ducted Prupulsor (IDP)

BOOK: Propeller / Shafting 91' Symposium

PUBLISHER: SNAME

Page Num: | **Vol.:** | **Date Published:** Sept. 1991

Report Num: | **Classification:** | **Ship Type:** | **Reference Type:**

Title: A New Type of Ship Energy-Saving Device..FPHFS fore-propeller hydrodynamical fin sector

Author(s) Name: Wenhao, Q., Z. Hanhum, and C. Yuejin

Keywords: Ducted Inflow Control Vanes; Reaction(tive) Fins

BOOK: Kansai Society of Naval Architects, Japan

PUBLISHER:

Page Num: | **Vol.:** No.218 | **Date Published:** Sept 1992

Report Num: | **Classification:** UNCL | **Ship Type:** | **Reference Type:** Technical Report

Title: Fin / Ducted Propeller - Hull Interaction

Author(s) Name: Oosterveld, M. W. C., E. J. Stierman, and J. Aufm Keller

Keywords: Ducted Propeller(s)

BOOK: International Maritime Innovative Symposium | **PUBLISHER:** SNAME

Page Num: | **Vol.:** | **Date Published:** Sept. 1984

Report Num: | **Classification:** UNCL | **Ship Type:** | **Reference Type:**

Title: An Analysis Method for a Ducted Propeller with Pre-Swirl Stator Blades

Author(s) Name: Hughes, M.J., and S.A. Kinnas

Keywords: Ducted Propeller; Stator Upstream of Propeller

BOOK: SNAME Propellers/Shafting '91 Symposium | **PUBLISHER:** SNAME

Page Num: | **Vol.:** | **Date Published:** Sept. 1991

Report Num: | **Classification:** UNCL | **Ship Type:** | **Reference Type:** Technical Report

Title: On the Optimization, Including Viscosity Effects, of Ship Screw Propellers with Optimal End Plates

Author(s) Name: DeJong, K.

Keywords: Energy Efficient Tip Propellers

BOOK: International Shipbuilding Progress | **PUBLISHER:**

Page Num: | **Vol.:** 38 | **Date Published:** 1991

Report Num: | **Classification:** UNCL | **Ship Type:** | **Reference Type:** Technical Report

Title: Design and Model Tests of Tip Fin Propellers

Author(s) Name: Andersen, P., and H. Schwaneke

Keywords: Energy Efficient Tip Propellers

BOOK: RINA Spring Meeting | **PUBLISHER:** RINA

Page Num: | **Vol.:** | **Date Published:** 1952

Report Num: | **Classification:** UNCL | **Ship Type:** 8 - Cargo/Auxiliaries | **Reference Type:** Technical Report

Title: The Evolution and Development of the Meridian Propeller

Author(s) Name: Patience, G. and L. Bodger

Keywords: Energy Efficient Tip Propellers

BOOK: Improving the Underwater Efficiency of Ships | **PUBLISHER:** Institute of Marine Engineers / Royal Institute of Naval

Page Num: | **Vol.:** 99 | **Date Published:** April 1987

Report Num: | **Classification:** | **Ship Type:** | **Reference Type:**

Title: Hydrofoil Benefits from Tip Loaded Propeller Retrofit

Author(s) Name:

Keywords: Energy Efficient Tip Propellers; Kappel Propellers; Concentrated Tip Loading (CLT) Propellers

BOOK: Marine Propulsion | **PUBLISHER:**

Page Num: | **Vol.:** | **Date Published:** April 1996

Report Num: | **Classification:** | **Ship Type:** | **Reference Type:**

Title: Blade Tip Loaded Propellers Adapted to the Fluid Vein Crossing Through the Propeller Disk

Author(s) Name: Perez Gomez, Dr. G.

Keywords: Energy Efficient Tip Propellers; Kappel Propellers; Concentrated Tip Loading (CLT) Propellers

BOOK: 6th Lips Propeller Symposium | **PUBLISHER:**

Page Num: | **Vol.:** | **Date Published:** May 1986

Report Num: | **Classification:** | **Ship Type:** | **Reference Type:**

Title: Sistemar's Propeller Claims are Backed

Author(s) Name: Perez Gomez, Dr. G.

Keywords: Energy Efficient Tip Propellers; Kappel Propellers; Concentrated Tip Loading (CLT) Propellers

BOOK: Sistemar Report, A Supplement of The Motorship | **PUBLISHER:** Reed Business Publishing Ltd.

Page Num: | **Vol.:** | **Date Published:** Sept. 1993

Report Num: | **Classification:** | **Ship Type:** | **Reference Type:**

Title: Experience with Retrofitted Propellers to Erships Bulkers

Author(s) Name: Perez Gomez, Dr. G., and Mr. Gonzalez-Adalid

Keywords: Energy Efficient Tip Propellers; Kappel Propellers; Concentrated Tip Loading (CLT) Propellers

BOOK: Sistemar Report, A Supplement of The Motorship | **PUBLISHER:** Reed Business Publishing Ltd.

Page Num: | **Vol.:** | **Date Published:** Sept. 1993

Report Num: | **Classification:** | **Ship Type:** | **Reference Type:**

Title: Retrofitting a Reefer Ship

Author(s) Name: Perez Gomez, Dr. and Mr. Gonzalez-Adalid

Keywords: Energy Efficient Tip Propellers; Kappel Propellers; Concentrated Tip Loading (CLT) Propellers

BOOK: Sistemar Report, A Supplement of The Motorship | **PUBLISHER:** Reed Business Publishing Ltd.

Page Num: | **Vol.:** | **Date Published:** Sept. 1993

Report Num: | Classification: | Ship Type: | Reference Type:

Title: First CLT Propeller Fitted in South Korea

Author(s) Name: Perez Gomez, Dr. G., and Mr. Gonzalez-Adalid

Keywords: Energy Efficient Tip Propellers; Kappel Propellers; Concentrated Tip Loading (CLT) Propellers

BOOK: Sistemar Report, A Supplement of The Motorship

PUBLISHER: Reed Business Publishing Ltd.

Page Num: | Vol.: | Date Published: Sept. 1993

Report Num: | Classification: | Ship Type: | Reference Type:

Title: Full - Scale Results of First TVF Propellers

Author(s) Name: Ruiz-Fornells, Dr. R. and Dr. G. Perez-Gomez

Keywords: Energy Efficient Tip Propellers; Kappel Propellers; Concentrated Tip Loading (CLT) Propellers

BOOK: International Symposium on Ship Hydrodynamics and Energy Saving

PUBLISHER:

Page Num: | Vol.: | Date Published: Sept 1983

Report Num: | Classification: | Ship Type: | Reference Type:

Title: Model Testing of an Optimally Designed Propeller with Two Sided Shifted End Plates on the Blades

Author(s) Name: Jong K. de, J. Sparenberg, J. Falcao de Campos, and W. van Gent

Keywords: Energy Efficient Tip Propellers; Kappel Propellers; Concentrated Tip Loading (CLT) Propellers

BOOK:

PUBLISHER:

Page Num: | Vol.: | Date Published:

Report Num: SPD-0829-27 | Classification: | Ship Type: | Reference Type:

Title: Evaluation of Various Propulsion Arrangements to Improve Energy Conservation for Naval Combatants - Summary Report

Author(s) Name: Reed, A.M., and W.G. Day, Jr.

Keywords: Energy Saving Devices

BOOK:

PUBLISHER: DTNSRDC

Page Num: | Vol.: | Date Published: May 1984

Report Num: | Classification: | Ship Type: | Reference Type:

Title: VECOM Very Economic Machinery-arrangement

Author(s) Name: Vulkan, B., H. Koestermann, and A. Nolte

Keywords: Energy Saving Devices

BOOK: Presentation on 19th September in Kristiansand/Norway

PUBLISHER:

Page Num: | Vol.: | Date Published: Sept 1984

Report Num: | Classification: | Ship Type: | Reference Type:

Title: Effectiveness of Various Types of Energy-Saving Devices Fitted in Sea-Going Ships

Author(s) Name: Kanevsky, G. I., O.P. Orlov, and V.M. Stumpf

Keywords: Energy Saving Devices

BOOK: PRADS 1989

PUBLISHER:

Page Num: | Vol.: 3 | Date Published: 1989

Report Num: | Classification: | Ship Type: | Reference Type:

Title: Fuel Efficiency Through Hull Form and Propulsion Research A Review of Recent MARIN Activities

Author(s) Name: Muntjewerf, J. J. and M.W.C. Oosterveld

Keywords: Energy Saving Devices

BOOK: Spring Meeting/STAR Symposium

PUBLISHER: The Society of Naval Architects and Marine Engineers

Page Num: | Vol.: | Date Published: May 1987

Report Num: | Classification: | Ship Type: | Reference Type:

Title: Thrust Augmentation Devices

Author(s) Name: Carlton, J. S.

Keywords: Energy Saving Devices

BOOK: Marine Propellers and Propulsion

PUBLISHER: Butterworth Heinemann

Page Num: | Vol.: | Date Published:

Report Num: | **Classification:** UNCL | **Ship Type:** | **Reference Type:** Technical Report

Title: Hydrodynamic Efficiency Improvements for U. S. Navy Ships

Author(s) Name: McCallum, D., A. H. Engle, G. P. Platzer, and G. Karafiath

Keywords: Energy Saving Devices

BOOK:

PUBLISHER: Naval Engineers Journal

Page Num: | **Vol.:** | **Date Published:** May 1991

Report Num: | **Classification:** UNCL | **Ship Type:** 8 - Cargo/Auxiliaries | **Reference Type:** Technical Report

Title: Improving the Propulsive Efficiency of Full Form Ships

Author(s) Name: Osborne, M. G.

Keywords: Energy Saving Devices

BOOK: Improving the Underwater Efficiency of Ships

PUBLISHER: Institute of Marine Engineers / Royal Institute of Naval

Page Num: | **Vol.:** 99 | **Date Published:** April 1987

Report Num: | **Classification:** UNCL | **Ship Type:** 8 - Cargo/Auxiliaries | **Reference Type:** Technical Report

Title: Propulsive Devices for Improved Propulsive Efficiency

Author(s) Name: Glover, E. J.

Keywords: Energy Saving Devices

BOOK: Improving the Underwater Efficiency of Ships

PUBLISHER: Institute of Marine Engineers / Royal Institute of Naval

Page Num: | **Vol.:** 99 | **Date Published:** April 1987

Report Num: | **Classification:** | **Ship Type:** | **Reference Type:**

Title: An Appraisal of Unconventional Aftbody Configurations and Propulsion Devices

Author(s) Name: Blaurock, J.

Keywords: Energy Saving Devices;
Grothues Spoiler
Wake Equalizing Duct (ZAD)
Vane (Grim) Wheel
Asymmetric Stern

BOOK: Marine Technology

PUBLISHER: The Society of Naval Architects and Marine Engineers

Page Num: | **Vol.:** 27 No.6 | **Date Published:** Nov 1990

Report Num: | **Classification:** | **Ship Type:** | **Reference Type:**

Title: The Design and Hydrodynamic Efficiency of Energy Saving Devices

Author(s) Name: Mishkevich, Dr. V.

Keywords: Energy Saving Devices;
Low RPM / Large Diameter Propeller
Contra-Rotating Propellers
Concentrated Tip Loading (CLT) Propellers
Wake Equalizing Duct
Boss Cap Fin

BOOK: 1994 Ship Operations, Management and Economics Symposium

PUBLISHER: The Society of Naval Architects and Marine Engineers

Page Num: | **Vol.:** | **Date Published:** May 1994

Report Num: | **Classification:** | **Ship Type:** | **Reference Type:** Book

Title: Ship Design for Efficiency and Economy

Author(s) Name: Schneekluth, H.

Keywords: Energy Savings Devices

BOOK:

PUBLISHER: Butterworth & Co.

Page Num: | **Vol.:** | **Date Published:** 1987

Report Num: | **Classification:** | **Ship Type:** | **Reference Type:**

Title: Bilge Vortex Control Devices and Their Benefits for Propulsion

Author(s) Name: Grothues - Spork, H.

Keywords: Flow Fins (Bilge Vortex)
Grothues (HDF) Spoiler
Profiled Strut Arms
Wake Adapting Fins

BOOK: International Shipbuilding Progress

PUBLISHER: Rotterdam, International Periodical Press

Page Num: | **Vol.:** 35 No.402 | **Date Published:** Jul 1988

Report Num: | **Classification:** | **Ship Type:** | **Reference Type:**

Title: Stern Flow Control by use of Bilge Rotors

Author(s) Name: Tokunaga, K.

Keywords: Flow Fins (Bilge Vortex)
Grothues (HDF) Spoiler
Profiled Strut Arms
Wake Adapting Fins

BOOK: Society of Naval Architects, Japan

PUBLISHER:

Page Num: | **Vol.:** no 69 | **Date Published:** 1985

Report Num: | **Classification:** | **Ship Type:** | **Reference Type:**

Title: An Experimental Study on the Ship Performance Improving Appendages

Author(s) Name: Lee, K. J., S. W. Joa, M. Park, and Y. W. Lee

Keywords: Flow Fins (Bilge Vortex); Grothues (HDF) Spoiler; Profiled Strut Arms; Wake Adapting Fins

BOOK: PRADS 1992 | **PUBLISHER:**

Page Num: | **Vol.:** | **Date Published:** 1992

Report Num: | **Classification:** | **Ship Type:** 8 - Cargo/Auxiliaries | **Reference Type:**

Title: Causes and Corrections for Propeller-Excited Airborn Noise on a Naval Auxiliary Oiler

Author(s) Name: Wilson, M.B., et al.

Keywords: Flow Fins on Hull

BOOK: SNAME Transactions | **PUBLISHER:** SNAME

Page Num: | **Vol.:** 90 | **Date Published:**

Report Num: | **Classification:** | **Ship Type:** 8 - Cargo/Auxiliaries | **Reference Type:**

Title: Translations from: Der Grothues-Spoiler als weiterer Beitrag zur Verbesserung der Propulsionseigenschaften von Einschrauben-Schiffen Hansa

Author(s) Name:

Keywords: Grothues Spoiler

BOOK: | **PUBLISHER:** Schiffahrt-Schiffbau-Hafen

Page Num: | **Vol.:** 121, No. 10 | **Date Published:** 1984

Report Num: | **Classification:** | **Ship Type:** | **Reference Type:**

Title: Development and full-scale experiences of a novel integrated duct propeller

Author(s) Name: Narita, H., et al.

Keywords: Hitachi - Zoden (HZ) Nozzle; Mitsui Integrated Duct (MIDP)

BOOK: SNAME Transactions | **PUBLISHER:** SNAME

Page Num: | **Vol.:** | **Date Published:** Nov. 1981

Report Num: | **Classification:** | **Ship Type:** | **Reference Type:**

Title: Hitachi's HZ nozzle: more efficient, more adaptable

Author(s) Name:

Keywords: Hitachi Zosen (HZ) Nozzle

BOOK: | **PUBLISHER:** The Motor Ship

Page Num: | **Vol.:** | **Date Published:** June 1981

Report Num: | **Classification:** | **Ship Type:** | **Reference Type:**

Title: Evaluation of various types of nozzle propeller and reaction fin as the device for the improvement of propulsive performance of high block coefficient ships

Author(s) Name: Takekuma, K.

Keywords: Hitachi Zosen (HZ) Nozzle; Mitsui Integrated Duct (MIDP); Wake Equalizing Duct (ZAD)

BOOK: Shipboard Energy Conservation Symposium | **PUBLISHER:** SNAME

Page Num: | **Vol.:** | **Date Published:** Sept. 1980

Report Num: | **Classification:** | **Ship Type:** 8 - Cargo/Auxiliaries | **Reference Type:**

Title: Wake Equalizing Ducts

Author(s) Name:

Keywords: Hitachi Zosen (HZ) Nozzle; Mitsui Integrated Duct (MIDP); Wake Equalizing Duct (ZAD)

BOOK: The Naval Architect | **PUBLISHER:** The Royal Institute of Naval Architects

Page Num: | **Vol.:** | **Date Published:** April 1986

Report Num: | **Classification:** | **Ship Type:** | **Reference Type:**

Title: Schneekluth Wake Equalizing Ducts for Twin-Screw ships

Author(s) Name:

Keywords: Hitachi Zosen (HZ) Nozzle; Mitsui Integrated Duct (MIDP); Wake Equalizing Duct (ZAD)

BOOK: The Naval Architect | **PUBLISHER:**

Page Num: | **Vol.:** | **Date Published:** Oct 1992

Report Num: | **Classification:** | **Ship Type:** | **Reference Type:**

Title: The Design of an Energy Saving, Wake Adapted Duct

Author(s) Name: Stierman, E. J.

Keywords: Hitachi Zosen (HZ) Nozzle; Mitsui Integrated Duct (MIDP); Wake Equalizing Duct (ZAD); Asymmetric Stern

BOOK: 3rd Intl. Symposium on Practical Design of Ships and Mobile Units | **PUBLISHER:** held Trondheim, Norway

Page Num: | **Vol.:** 1 | **Date Published:** June 1987

Report Num: | **Classification:** | **Ship Type:** | **Reference Type:**

Title: The Wake Equalizing Duct

Author(s) Name: Schneekluth, H.

Keywords: Hitachi Zosen (HZ) Nozzle; Mitsui Integrated Duct (MIDP); Wake Equalizing Duct (ZAD)

BOOK: Applications of New Technology in Shipping | **PUBLISHER:** Marine Management (Holdings)

Page Num: | **Vol.:** | **Date Published:** May 1989

Report Num: | **Classification:** | **Ship Type:** | **Reference Type:**

Title: Wake Equalizing Duct, State of Development

Author(s) Name: Schneekluth, H.

Keywords: Hitachi Zosen (HZ) Nozzle; Mitsui Integrated Duct (MIDP); Wake Equalizing Duct (ZAD)

BOOK: 6th Lips Propeller Symposium

PUBLISHER:

Page Num: | **Vol.:** | **Date Published:** May 1986

Report Num: | **Classification:** | **Ship Type:** | **Reference Type:**

Title: Hydrodynamic Models for the Design of the Energy Saving Devices

Author(s) Name: Popovici, J. S., St. Totolici, M. Popa, and V. Ceanga

Keywords: Hitachi Zosen (HZ) Nozzle; Mitsui Integrated Duct (MIDP); Wake Equalizing Duct (ZAD)

BOOK: PRADS 1989

PUBLISHER:

Page Num: | **Vol.:** | **Date Published:** 1989

Report Num: | **Classification:** | **Ship Type:** | **Reference Type:**

Title: Effect of Tip Clearance Extreems on Cavitation and Unsteady Hull Pressure Excitation

Author(s) Name: Wilson, M.B., K.J. Anderson, and C.C. Hsu

Keywords: Low RPM / Large Dia Propellers

BOOK: Transcripts of CAV'95 International Symposium on Cavitation

PUBLISHER:

Page Num: | **Vol.:** | **Date Published:** May 1995

Report Num: | **Classification:** | **Ship Type:** | **Reference Type:**

Title: Developments in Marine Propellers

Author(s) Name: Patience, G.

Keywords: Low RPM / Large Dia Propellers

BOOK: Journal of Power and Energy

PUBLISHER: IMechE 1991

Page Num: | **Vol.:** | **Date Published:** 1991

Report Num: 1103 | **Classification:** | **Ship Type:** | **Reference Type:**

Title: Experiments on propulsive arrangements with slow turning large diameter propellers

Author(s) Name: Della Loggia, B., L. Doria, and S. Cappelli

Keywords: Low RPM / Large Diameter Propeller

BOOK:

PUBLISHER: CETENA

Page Num: | **Vol.:** | **Date Published:**

Report Num: | **Classification:** UNCL | **Ship Type:** | **Reference Type:** Technical Report

Title: Improvement of Surface Ship Propeller Cavitation Performance Using Advanced Blade Sections

Author(s) Name: Bailar, J.W., S.D. Jessup, and Y.T. Shen

Keywords: New Propeller Design

BOOK: Proceedings of the Twenty-Third ATTC

PUBLISHER: ATTC

Page Num: | **Vol.:** | **Date Published:** June 1992

Report Num: | **Classification:** | **Ship Type:** | **Reference Type:**

Title: Hydrodynamic Design of Propellers with Unconventional Geometry

Author(s) Name: Anderson, S.V., and P Anderson

Keywords: New Propeller Design

BOOK: Transactions Royal Institute of Naval Architecture

PUBLISHER: RINA

Page Num: | **Vol.:** | **Date Published:** 1987

Report Num: | **Classification:** | **Ship Type:** | **Reference Type:**

Title: In Persuit of the Elusive "Perfect" Propeller Solution

Author(s) Name:

Keywords: New Propeller Design

BOOK: Marine Log

PUBLISHER:

Page Num: | **Vol.:** | **Date Published:** May 1966

Report Num: | **Classification:** | **Ship Type:** ? | **Reference Type:**

Title: Development and Assessment of a Total Resistance Optimized Bow for the AE-36

Author(s) Name: Wyatt, D.C., and P.A. Chang, III

Keywords: Numerically Optimized Forebody

BOOK: International Symposium on CFD and CAD in Ship Design

PUBLISHER:

Page Num: | **Vol.:** | **Date Published:** Sept. 1990

Report Num: | **Classification:** | **Ship Type:** | **Reference Type:**

Title: Technology for saving power with an off-centre propeller

Author(s) Name: NKK Corporation

Keywords: Off Center Propeller

BOOK:

PUBLISHER: documant supplied by The British Library Document

Page Num: | **Vol.:** | **Date Published:**

Report Num: | **Classification:** | **Ship Type:** 8 - Cargo/Auxiliaries | **Reference Type:**

Title: Propulsion, cavitation and vibration characteristics of overlapping propellers for a containership

Author(s) Name: Kerlen, H. et al.

Keywords: Overlapping Propellers

BOOK:

PUBLISHER: International Shipbuilding Progress

Page Num: | **Vol.:** 19,No. 214 | **Date Published:** June 1972

Report Num: | **Classification:** | **Ship Type:** | **Reference Type:**

Title: Experimental study on the twin-skeg overlapping propeller system

Author(s) Name: Min, K.S.

Keywords: Overlapping Propellers
Twin Skegs

BOOK: 6th Lips Propeller Symposium

PUBLISHER:

Page Num: | **Vol.:** | **Date Published:** May 1986

Report Num: | **Classification:** | **Ship Type:** | **Reference Type:**

Title: Performance Assessment of Propeller Boss Cap Fin Type Device

Author(s) Name: Gearhart, W.S., and M.W. McBride

Keywords: Propeller Boss Cap Fin

BOOK: 22nd American Towing Tank Conference

PUBLISHER: ATTC

Page Num: | **Vol.:** | **Date Published:**

Report Num: | **Classification:** | **Ship Type:** | **Reference Type:**

Title: Propeller Boss Cap Fin Enhances Efficiency

Author(s) Name: Ouchi, K.

Keywords: Propeller Boss Cap Fin

BOOK:

PUBLISHER:

Page Num: | **Vol.:** | **Date Published:**

Report Num: TSC-35.5-1 | **Classification:** | **Ship Type:** 3 - Destroyers | **Reference Type:**

Title: Effect of Pitch Scheduling on Fuel Usage for Gas Turbine Ships: USS Spruance (DD-963) Sea Trials

Author(s) Name: Hansen, A.G., and N. Santelli

Keywords: Propeller Pitch Scheduling

BOOK:

PUBLISHER: The Scientex Corp.

Page Num: | **Vol.:** | **Date Published:** Nov. 1983

Report Num: **Classification:** **Ship Type:** **Reference Type:** Technical Report

Title: Experience with Controllable Pitch Propellers During Full Scale Performance and Special Trials

Author(s) Name: Klitsch, M. L., R. J. Stenson, and E. L. Woo

Keywords: Propeller Pitch Scheduling; Controllable Pitch Propellers

BOOK: Proceedings of Ninth Ship Control Systems Symposium **PUBLISHER:**

Page Num: **Vol.:** **Date Published:** Sept 1990

Report Num: **Classification:** **Ship Type:** **Reference Type:**

Title: Postswirl Propulsors - A Design Method and an Application

Author(s) Name: Chen, B.Y-H.

Keywords: Stator Behind Propeller

BOOK: **PUBLISHER:** International Symposium on Propulsors and Cavitation

Page Num: **Vol.:** **Date Published:** June 1992

Report Num: **Classification:** **Ship Type:** **Reference Type:**

Title: Design Method and Application of an Asymmetric Stator Upstream of a Inclined Shaft Propeller

Author(s) Name: Neeley, S.K., J. McMahon, and B.Y-H. Chen

Keywords: Stator Upstream of Propeller

BOOK: Transactions 23rd American Towing Tank Conference **PUBLISHER:** ATTC

Page Num: **Vol.:** **Date Published:** 1993

Report Num: **Classification:** **Ship Type:** **Reference Type:**

Title: Propeller Erosion Reduction with an Asymmetric Preswirl Stator

Author(s) Name: Smith, T.B., and K.D. Remmers

Keywords: Stator Upstream of Propeller

BOOK: Transactions 23rd American Towing Tank Conference **PUBLISHER:** ATTC

Page Num: **Vol.:** **Date Published:** 1993

Report Num: **Classification:** UNCL **Ship Type:** **Reference Type:** Technical Report

Title: Pre - Swirl Stator and Propeller / Stator Efficiency

Author(s) Name: Gaafary, M. M., and M. M. Mosaad

Keywords: Stator Upstream of Propeller

BOOK: Propeller / Shafting 91' Symposium **PUBLISHER:** SNAME

Page Num: **Vol.:** **Date Published:** Sept. 1991

Report Num: **Classification:** **Ship Type:** **Reference Type:**

Title: Resistance Reduction by Stern-End-Bulb

Author(s) Name: Hideaki, M., and others

Keywords: Stern End Bulbs

BOOK: Journel of the Society of Naval Architects of Japan **PUBLISHER:** JSNAME

Page Num: **Vol.:** **Date Published:** 1980-1982

Report Num: **Classification:** **Ship Type:** **Reference Type:**

Title: Resistance Reduction by Stern-End-Bulb (Second report)

Author(s) Name: Miyata, H., T. Inui, and Y. Tsuchiya

Keywords: Stern End Bulbs

BOOK: J. of the Society of Naval Architects of Japan **PUBLISHER:**

Page Num: **Vol.:** 149 **Date Published:** 1981

Report Num: **Classification:** **Ship Type:** **Reference Type:**

Title: Resistance Reduction by Stern-End-Bulb (First report)

Author(s) Name: Miyata, H., T. Inui, Y. Tsuchiya, and H. Adachi

Keywords: Stern End Bulbs

BOOK: J. of the Society of Naval Architects of Japan **PUBLISHER:**

Page Num: **Vol.:** 148 **Date Published:** 1980

Report Num: | **Classification:** | **Ship Type:** | **Reference Type:**

Title: Resistance Reduction by Stern-End-Bulb (Third report)

Author(s) Name: Okamoto, H., A. Tanaka, T. Yamano, H. Miyata, T. Inui, and Y. Tsuchiya

Keywords: Stern End Bulbs

BOOK: J. of the Society of Naval Architects of Japan | **PUBLISHER:**

Page Num: | **Vol.:** | **Date Published:**

Report Num: | **Classification:** | **Ship Type:** 8 - Cargo/Auxiliaries | **Reference Type:**

Title: Survey and Analysis of Existing Information on the Effects of Stern End Bulbs on Merchant Ships

Author(s) Name: Ward, L. W., and R.D. Sedat

Keywords: Stern End Bulbs

BOOK: Center for Maritime Studies | **PUBLISHER:** Webb Insitute of Naval Architecture

Page Num: | **Vol.:** | **Date Published:** Oct 1984

Report Num: | **Classification:** | **Ship Type:** | **Reference Type:**

Title: Some Methods to Reduce Stern Waves

Author(s) Name: Yamano, T., Y. Iwasaki, K. Taguchi, and N. Maeda

Keywords: Stern End Bulbs

BOOK: 5th International Marine Design Conference | **PUBLISHER:**

Page Num: | **Vol.:** | **Date Published:** May 1994

Report Num: | **Classification:** UNCL | **Ship Type:** 7 - Patrol Craft | **Reference Type:** Technical Report

Title: Stern Flap Powering Performance on PC 1 Patrol Coastal, Ship Trials and Model Experiments

Author(s) Name: Cusanelli, D. S.

Keywords: Stern Flap

BOOK: PATROL '96 Conference, New Orleans, LA | **PUBLISHER:**

Page Num: | **Vol.:** | **Date Published:** Dec. 1996

Report Num: | **Classification:** | **Ship Type:** | **Reference Type:**

Title: The Effect of Stern Wedges on Ship Powering Performance

Author(s) Name: Karafiath, G. and S. C. Fisher

Keywords: Stern Flap, Stern Wedge

BOOK: Naval Engineers Journal | **PUBLISHER:**

Page Num: | **Vol.:** | **Date Published:** May 1987

Report Num: | **Classification:** UNCL | **Ship Type:** ? | **Reference Type:**

Title: Effect of Stern Flaps on Powering Performance of the FFG-7 Class

Author(s) Name: Cave, W. L. III, and D. S. Cusanelli

Keywords: Stern Flap, Stern Wedge

BOOK: Marine Technology | **PUBLISHER:** Society of Naval Architects and Marine Engineers

Page Num: | **Vol.:** 30 No.1 | **Date Published:** Jan 1993

Report Num: Ref # 31635 | **Classification:** | **Ship Type:** | **Reference Type:**

Title: Twin Stern Ship for Energy Saving

Author(s) Name: Shimo, L.

Keywords: Twin Skegs

BOOK:

PUBLISHER: Wuhan University of Water Transportation Engineering

Page Num: | **Vol.:** | **Date Published:**

Report Num: | **Classification:** | **Ship Type:** 11 - Passengers/Liners | **Reference Type:**

Title: The Application of Twin-Stern shipform to River Passenger Ships

Author(s) Name: Hua, Y. F.

Keywords: Twin Skegs

BOOK: Ship and Boat International

PUBLISHER:

Page Num: | **Vol.:** | **Date Published:** March 1987

Report Num: | **Classification:** | **Ship Type:** | **Reference Type:**

Title: Energy - Saving Shaft Bracket for Multi-Screw Ships

Author(s) Name: Zhanming, Z. and Z. Hanhun

Keywords: Twin Skegs

BOOK: Selected Papers of CSNAME

PUBLISHER:

Page Num: | **Vol.:** 5 | **Date Published:** 1990

Report Num: 181 | **Classification:** UNCL | **Ship Type:** ? | **Reference Type:** Technical Report

Title: Study of the Hull Form with "Catamran Stern" - Applied to Tanker / Bulk Carrier

Author(s) Name: Hanawa, T., S. Ogino, Y. Hashimoto, M. Mukai, and Y. Tsutada

Keywords: Twin Skegs

BOOK:

PUBLISHER: Kansai Society of Naval Architects

Page Num: | **Vol.:** | **Date Published:** June 1981

Report Num: | **Classification:** | **Ship Type:** | **Reference Type:**

Title: Propeller and Vane Wheel

Author(s) Name: Grim, O.

Keywords: Vane (Grim) Wheel

BOOK: Second George Weinblum Memorial Lecture, Journal of Ship

PUBLISHER: SNAME

Page Num: | **Vol.:** 24, No. 4 | **Date Published:** Dec. 1980

Report Num: | **Classification:** | **Ship Type:** | **Reference Type:**

Title: Free Rotating Propeller Installed on Ship

Author(s) Name: Kubo, H., M. Nagase, Y. Itadani, J. Omori, and M. Yoshioka

Keywords: Vane (grim) Wheel

BOOK: Marine Engineering Society Bulletin, Japan

PUBLISHER:

Page Num: | **Vol.:** 16, No.1 | **Date Published:** 1988

Report Num: | **Classification:** | **Ship Type:** | **Reference Type:**

Title: Propeller Plus Vane Wheel, An Unconventional Propulsion System

Author(s) Name: Blanrock, J.

Keywords: Vane (Grim) Wheel

BOOK: Int. Symposium on Ship Hydrodynamics and Energy Saving

PUBLISHER:

Page Num: | **Vol.:** | **Date Published:** Sept. 1983

Report Num: | **Classification:** | **Ship Type:** | **Reference Type:**

Title: The Grim-Wheel Reports and Experiences

Author(s) Name: vom Baur, M., and K. J. Meyne

Keywords: Vane (Grim) Wheel

BOOK: HANSA

PUBLISHER:

Page Num: | **Vol.:** | **Date Published:** 1984

Report Num: | **Classification:** | **Ship Type:** | **Reference Type:**

Title: Divers face Grim damage

Author(s) Name: Doughty, P.

Keywords: Vane (Grim) Wheel

BOOK: Shiprepair, A Supplement of the MotorShip

PUBLISHER: Reed Business Publishing

Page Num: | **Vol.:** | **Date Published:** March 1996

Report Num:

Classification: UNCL

Ship Type:

Reference Type:

Title:
Designing Vane Wheel Systems

Author(s) Name:
de Cock, J.

Keywords:
Vane (Grim) Wheel

BOOK:

PUBLISHER: Schiff & Hafen / Kommandobrucke, Heft

Page Num:

Vol.:

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